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Ontario Geological Survey
Open File Report 6145

Summary of Field Work and Other Activities 2004

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ONTARIO GEOLOGICAL SURVEY

Open File Report 6145

Summary of Field Work and Other Activities 2004

by

C.L. Baker, E.J. Debicki, J.R. Parker, R.I. Kelly, J.A. Ayer and R.M. Easton

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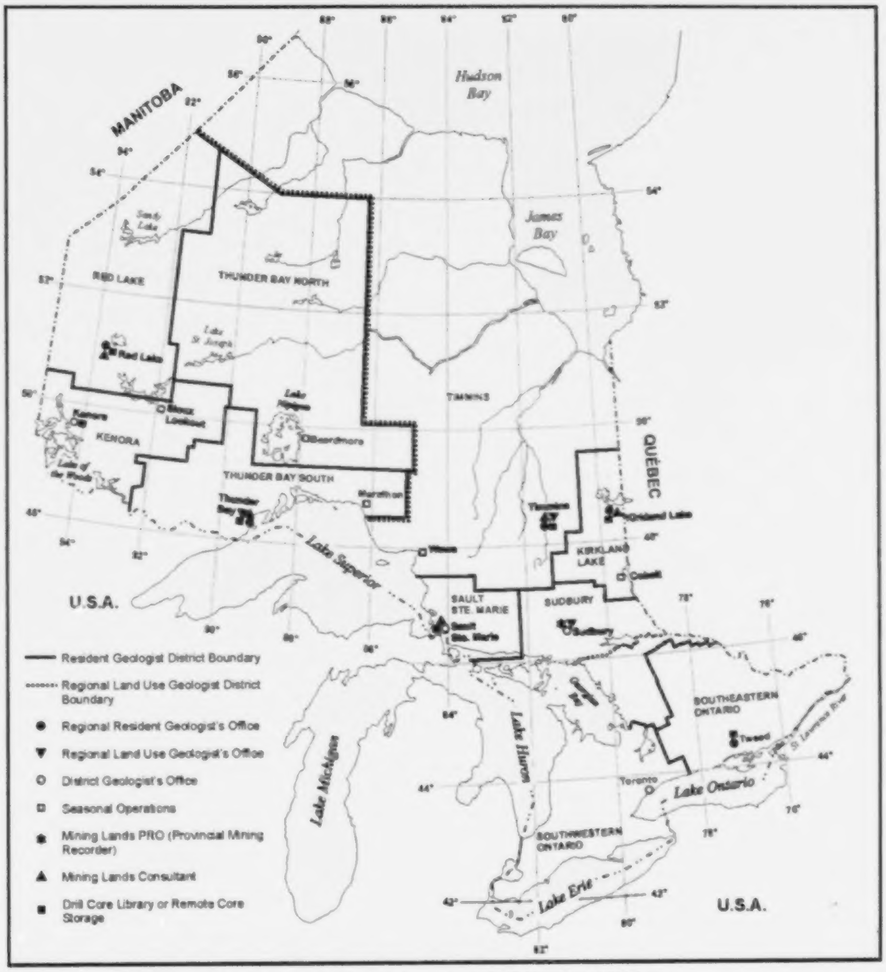
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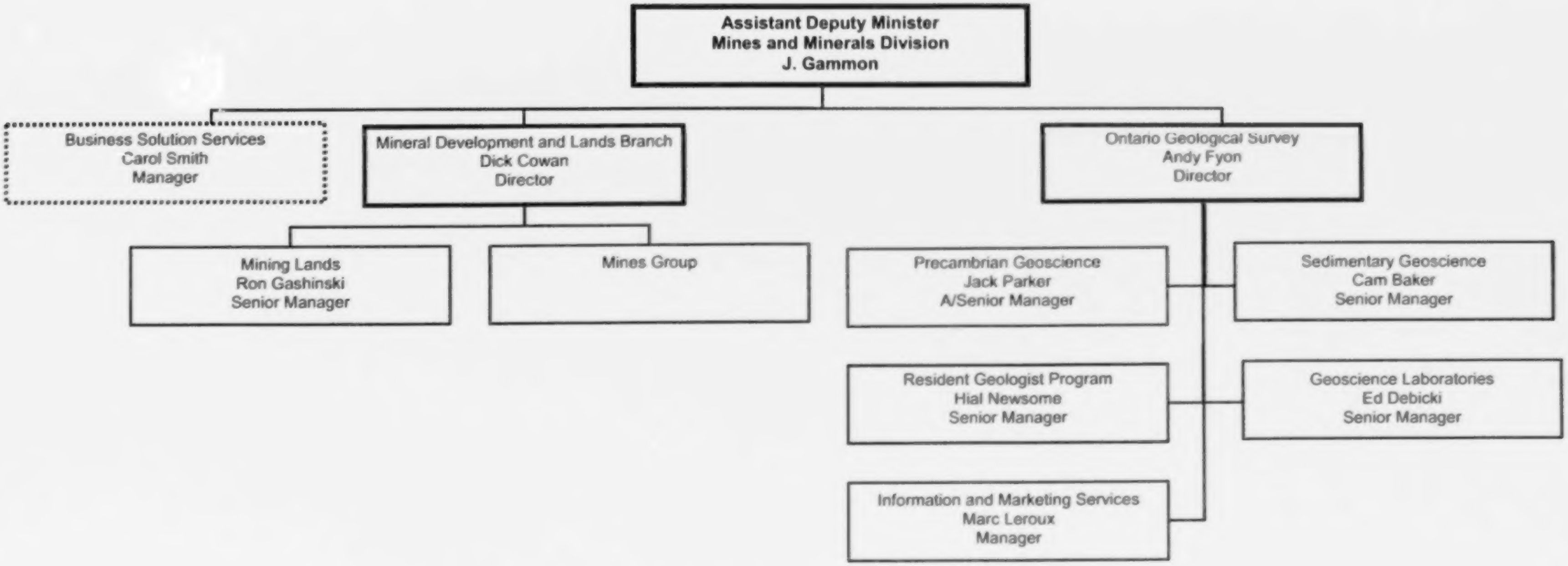
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1. The Ontario Geological Survey Branch — Reconstituted

J.A. Fyon[1]

[1]Director, Ontario Geological Survey

INTRODUCTION

On August 1, 2004, the Ontario Geological Survey (OGS) Branch was reconstituted by the integration of 5 business units: the Geoscience Laboratories, Information and Marketing Services Section, Precambrian Geoscience Section, Resident Geologist Program, and Sedimentary Geoscience Section (Figure 1.1).

The OGS is

- the expert provincial organization on regional to local, framework, geoscience data, information, and knowledge about Ontario;
- a principled and professional organization that operates with integrity;
- a supplier of credible and objective geoscience data and knowledge;
- a deliverer of products in time and forms that meet the client needs for quality and accuracy within the limits of our capacity and resources.

MANDATE AND CORE BUSINESS

The OGS delivers the Provision of Geoscience and Information Services Program, one of four programs under the Ministry of Northern Development and Mines' core business of Mineral Sector Competitiveness. The goal of the Mineral Sector Competitiveness core business is to enhance and to ensure the sustainable development of Ontario's mineral resources. This goal is achieved by promoting a healthy business climate that encourages and attracts mineral investment, exploration and mine development, and by undertaking targeted geoscience initiatives. OGS products stimulate investment attraction, help reduce exploration risk, and contribute to formulation of informed public policy and protection of public health and safety. In recent years, the OGS expanded its activities to support other government objectives, such as groundwater mapping for Safe Drinking.

PRIORITIES

Over the next year, the OGS will focus on several priorities to maintain its client service capacity. It is a priority to build on existing strengths to enhance the integration and cohesiveness of the OGS Branch. We will encourage Branch cohesiveness through integrated strategic and program planning and priority setting.

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Ontario faces some major planning and development challenges related to mineral resource access and development, groundwater resources, and security of energy supply. Consideration and incorporation of OGS geoscience data and knowledge into decision-making processes will help address these planning and development challenges. To broaden the reach of OGS products and services, it is important to work with new strategic decision-makers and clients to establish awareness and confidence in OGS data and services.

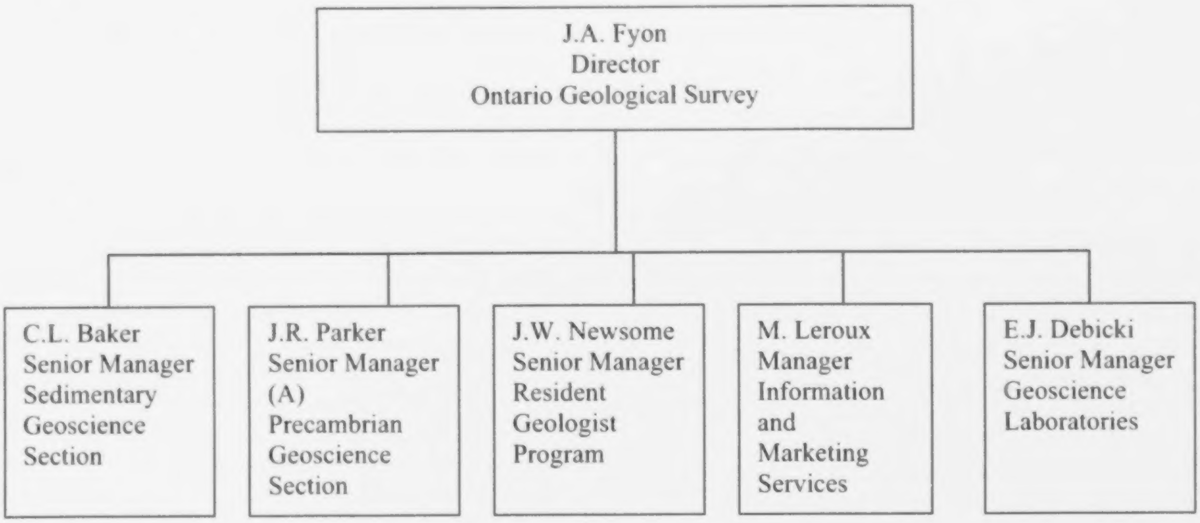
Clients ask for accurate, accessible geoscience data in a form that can be easily searched and easily integrated into other software applications. Over the next 3 years, the OGS Branch, working with the Business Solutions Section, will enhance client access to our data and products through the redesign of our geoscience data portal and transformation of key data sets. We will continue to market Ontario's mineral potential to attract new mineral investment and enhance Ontario's competitiveness. We now have the opportunity to efficiently implement our marketing strategy and tactics as a unified Branch. To demonstrate the impact of the geoscience and marketing activities, the OGS will continue to work with clients to demonstrate value for the public investment in the OGS.

Innovation, personal growth, and corporate growth are stimulated through collaboration and partnership work. Collaboration and partnership are also a means to apply specialized resources from several jurisdictions to address complex technical or social issues. The OGS will continue to work in collaboration and partnership where that is the most appropriate technical and political approach. We anticipate continued and new collaborations and partnerships with other Ministries, other Governments, academe, mineral industry companies and associations, and First Nations. The OGS will review and refine existing partnership practices to ensure a consistent Branch approach, to remove ambiguity, and to provide certainty to our existing and new partners.

OGS has a pan-provincial mandate, but Ontario's Far North represents one of our last development frontiers. The Far North is the target of the MNDM's "Creating Northern Prosperity" strategic direction. The Far North represents approximately 50% of Ontario by area, is the home of approximately 40 remote First Nation communities, and is characterized by favourable geology and inferred favourable mineral potential; mineral exploration activities are escalating, and a potential electricity transmission line through the north is under discussion. There is a need for northern geoscience as part of integrated northern planning, yet large areas of the north have never been mapped. In addition, remote First Nation communities, who fear they have been left outside of traditional development processes, have declared they want to be part of the present and future development. The Government stated its intent to improve relationships with First Nations. To contribute to this Government priority, OGS will continue working with First Nations to enhance communication, build relationships, and transfer technical knowledge about the local geology, the mineral industry, and prospecting techniques. These activities help lay a foundation for northern geoscience required to plan for future development.

I am excited about the future of the OGS Branch. The new and dynamic geoscience reported in this volume is a testament to the quality and dedication of the OGS staff. Challenges do exist, but with the input from the OGS Advisory Board, our traditional and new clients, and the continued efforts of dedicated OGS staff, the OGS Branch will continue to deliver high-quality geoscience that meets the Government priorities and stakeholder needs.

Figure 1.1. Ontario Geological Survey organizational chart.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2. Understanding, Communication and Mutual Respect: The Foundation for Partnership—An Approach to Working in Ontario's Far North

L.L. Churchill[1] and J.A. Fyon[2]

[1]Precambrian Geoscience Section, Ontario Geological Survey
[2]Ontario Geological Survey

INTRODUCTION

To conduct business successfully anywhere in the world, there must first be a solid foundation to work from. However, the best-laid foundation is nothing without communication, a relationship and commitment to move together toward common goals. Building a mutual understanding and learning to communicate between parties are instrumental to effective partnerships and are an investment in the future. It is strategic to learn to communicate and to achieve an understanding before it is possible to address an issue or decide how both parties can move forward together.

The Ontario Geological Survey (OGS) has participated in and will continue to foster communication practices and relationships with several First Nation communities located in northwestern Ontario in advance of our geological mapping activities (Fyon and Churchill 2003). The focus of this article is to report on OGS–First Nation engagement practices and experiences. Key success factors that lead to a strong working relationship with remote First Nations include

- Identifying common values and principles required to guide the delivery of the project or that guide the efforts
- An understanding of each party's expectations regarding the meaning of communication
- Committed and dedicated staff with the individual and organizational capacity to meet those communication expectations
- Required technical and social skills, knowledge and competencies
- Required financial and human resources

CONTEXT

Operating in remote parts of Ontario is challenging. Over 40% of Ontario's Far North has little or no all-season road infrastructure and has been used historically by First Nations to carry out traditional activities such as fishing, hunting and gathering. Economic opportunities for remote communities are limited; however, because of the mineral potential of this frontier area, mineral exploration activities are escalating. For many remote First Nation communities, understanding these exploration activities is challenging because

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1. the activities and the technical terms describing the activities are complex and new to many First Nation people
2. communication across cultures and organizations can be difficult because each culture may have different expectations and different decision-making and information exchange processes. It is important to bridge these differences for communication to become effective.

Several First Nations have issued moratoria on resource development. However, many First Nations have stated they are not against development. Rather, they want to participate in the decisions affecting development and share in the benefits flowing from development.

Recognizing the value of engaging First Nations, OGS implemented, in 1999, the practice of engaging First Nation communities located in areas where OGS conducts, or plans to conduct, geological mapping.

COMMUNICATION MODEL

The following is a brief review of the OGS–First Nation communication model (Fyon and Churchill 2003):

- Chief-to-Chief: Many MNDM senior executives and senior managers have travelled to, and met with, the Chiefs, Councillors and members of First Nation communities. The OGS attempts to ensure the presence of senior management at all decision-making meetings.
- Technical-to-Technical: Where meeting items are technical in nature, OGS attempts to ensure the presence of technical staff knowledgeable about the item or representative of the project.
- Community-to-Community: Mixed gender teams and non-technical members of our OGS team allow for input from, and communication with, a broader representation of a First Nation community. This broader source of community-level information increases awareness both within government and within the First Nation. This non-technical OGS person has remained the contact for ongoing and routine communication between the First Nation and the OGS.

To build trust in a partnership and maximize information exchange, it is important to have the same individuals involved throughout the duration of the partnership. There must be a common understanding and appreciation of the respective organizations. It is important to understand decision-making processes and how best to communicate. This can be achieved through long-term commitment and the establishment of relationships between people. This personal relationship facilitates resolution of items before they become issues and build upon successes.

The communities working with OGS include Eabametoong First Nation, Webequie First Nation, Kasabonika Lake First Nation, Neskantaga First Nation, and Marten Falls First Nation. The process of communication and relationship building differs for each community. That uniqueness of process reflects the community-specific needs and preferences.

COMMUNICATION TOOLS

No single information tool is capable of increasing awareness of government geological survey activities and mining sequence activities. It is important to work with each First Nation to determine which types of tools would best suit the needs of each respective community.

Translating the information to the local dialect is beneficial. The benefit comes from having the information presented in the local dialect and from the translation process where several community members may be involved and, therefore, acquire a better understanding of the meaning of technical words. Most post-European and geological or technical words must be described. For example, describing a word like "geophysical" typically involves several community members to determine the best descriptive phrase. This approach increases awareness and understanding of the information being shared among many people.

Memorandum of Co-operation

The OGS is currently working under the auspices of Memoranda of Co-operation (MOC) with Eabametoong First Nation and Webequie First Nation. The intent of the MOC is to improve communication and to increase awareness of First Nations about MNDM-OGS activities. In addition, MNDM–OGS acquires an increased awareness about traditional First Nation values and needs.

Geological and Mining Sequence Video

The OGS is representing Ontario's interests in partnership with Natural Resources Canada to develop a video (DVD and VHS) that objectively describes the activities that take place during government geological mapping and during the various stages of the mining sequence, that is, prospecting, early exploration, advanced exploration, mine development and operations, mine closure and rehabilitation. The intent is to describe these activities clearly and objectively. It is anticipated that this video will complement the video released earlier this year by the Ontario Mining Association.

The development of the video script, the activities and the actual filming was done co-operatively with several First Nations, prospectors, mineral exploration companies and mining companies. Most of the filming was conducted on active mineral exploration and mine sites and in those First Nation communities that are experiencing activities related to a specific stage of the mining sequence.

The video will be available in English, Ojibway, Cree, Oji-Cree and French. The anticipated release date of the video is March 2005.

Posters, Open Houses, and Presentations

The OGS in partnership with many of our First Nation partners has created posters, story boards, and presentations for delivery in the First Nation Communities, mines and minerals symposia and government functions to broaden the outreach to increase awareness to participants from all sectors of their respective views. The posters present most of the information visually, through the use of pictures, diagrams or figures.

Glossary of Geological and Mining Terms

The OGS in partnership with Eabametoong First Nation created a glossary of geological and mining terms. The process of creating this glossary involved community members ranging from the school children, who selected pictures and figures to best represent the words, to the elders who met to determine the best description of the English word, in the local Ojibway dialect. Each English word was given an English definition, a pictorial representation and translated into local dialect Ojibway syllabics and phonetics.

COMMUNICATION BENEFITS

It is our experience that business risk can be managed with more certainty and operational opportunities established with investment in communication and relationship-building practices (Fyon and Churchill 2003). Over the past year, the OGS in partnership with Far North First Nations have built upon and strengthened our practices to reflect the successes and challenges faced. The benefits include

- Reduced misunderstandings and reduced confrontation
- New knowledge for both parties
- Consistent OGS decision making
- Improved operational climate
- Communities that are better informed to make decisions about economic development options
- Foundation to address more controversial issues
- Outreach to other areas of government to share experiences
- Outreach to other First Nations to share experiences
- Informed and balanced land-use decision-making
- Improved business climate where dialogue between First Nation bands and mineral industry are entering into partnerships

SUMMARY

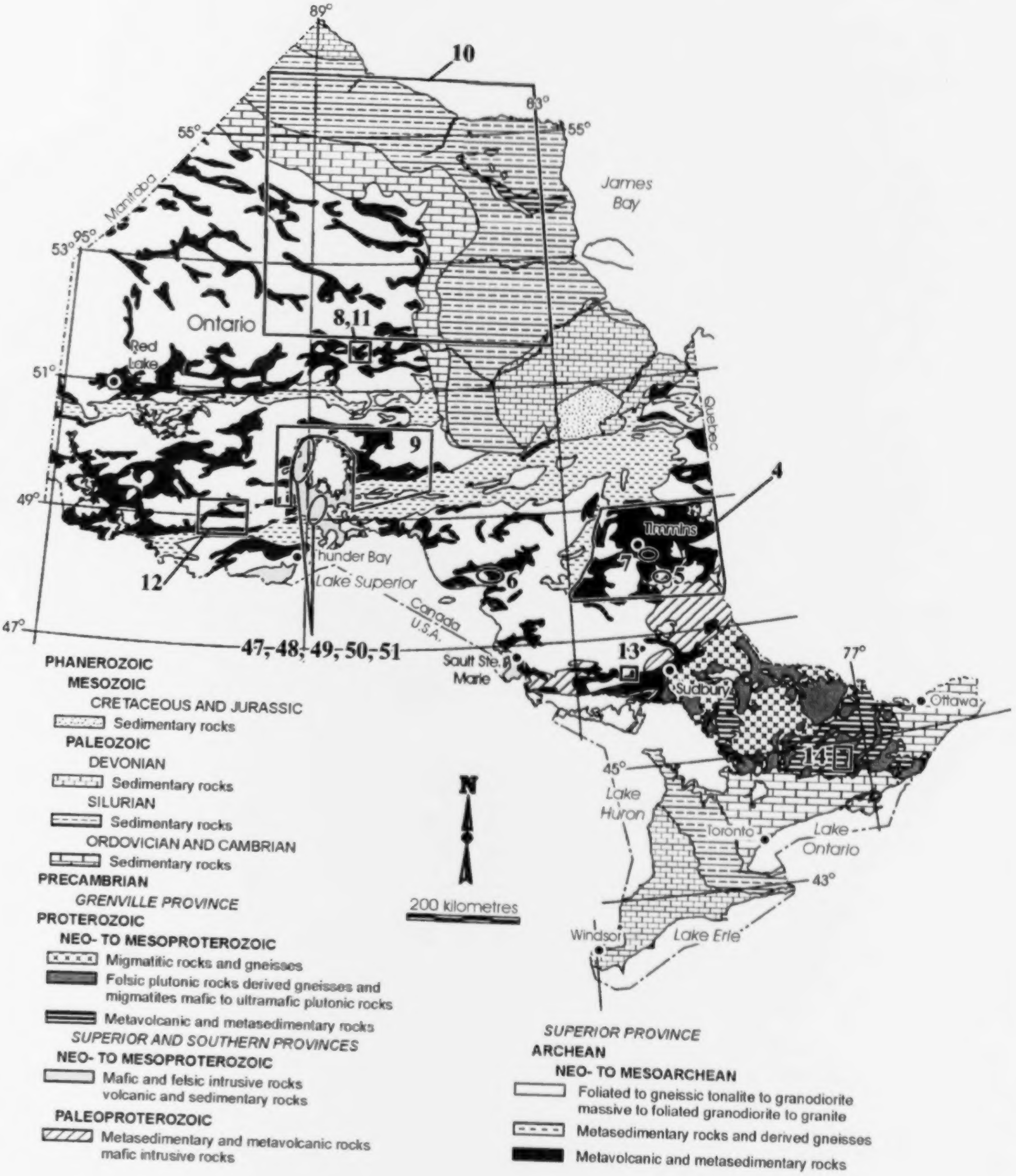
The OGS in partnership with our First Nations will continue to foster communication practices and relationship building where there is an operational interest in a region. Experiences gained to date include

- Identification of common values and principles constitute an important foundation to build upon
- The ability to communicate effectively can only be realized when communication tools and approaches are developed in partnership to address the common needs
- Having the right skills, knowledge and competencies to explore and co-develop communication processes is imperative. There is no single approach.
- Committed staff dedicated to communication and relationship building is necessary. Staff must be committed to the broader goal of communication and relationship building, realizing that there is a far larger picture at stake than the particular project that may have brought them to the table. Many First Nations state that involvement of the same staff in the process is an important success factor. Changing the players involved in a project may damage the results of efforts invested to that point.
- Financial and human resources required to carry out the project should be committed to see the project to completion. The time required to deliver a communication project is long-term. Relationships are not developed during a one-hour meeting. Relationship building is established through interaction that can only occur face-to-face. Organizations should view this investment in communication and relationship building as a long-term investment with tangible and intangible benefits.

REFERENCE

Fyon, J.A. and Churchill, L.L. 2003. Building relationships and improving communications with First Nation communities—an operational approach; *in* Summary of Field Work and Other Activities 2003, Ontario Geological Survey, Open File Report 6120, p.4-1 to 4-10.

Precambrian Geoscience Section


89°
10
83°
55°
55°
James Bay
Manitoba
53°
95°
Ontario
8,11
Red Lake
51°
Quebec
9
4
49°
Timmins
7
5
6
12
Thunder Bay
Lake Superior
Canada
U.S.A.
47°
47–48–49–50–51
Sault Ste. Marie
13
Sudbury
77°
Ottawa
14
45°
Lake Huron
Toronto
Lake Ontario
43°
Windsor
Lake Erie
N
200 kilometres
PHANEROZOIC
MESOZOIC
CRETACEOUS AND JURASSIC
Sedimentary rocks
PALEOZOIC
DEVONIAN
Sedimentary rocks
SILURIAN
Sedimentary rocks
ORDOVICIAN AND CAMBRIAN
Sedimentary rocks
PRECAMBRIAN
GRENVILLE PROVINCE
PROTEROZOIC
NEO- TO MESOPROTEROZOIC
Migmatitic rocks and gneisses
Felsic plutonic rocks derived gneisses and migmatites mafic to ultramafic plutonic rocks
Metavolcanic and metasedimentary rocks
SUPERIOR AND SOUTHERN PROVINCES
NEO- TO MESOPROTEROZOIC
Mafic and felsic intrusive rocks volcanic and sedimentary rocks
PALEOPROTEROZOIC
Metasedimentary and metavolcanic rocks mafic intrusive rocks
SUPERIOR PROVINCE
ARCHEAN
NEO- TO MESOARCHEAN
Foliated to gneissic tonalite to granodiorite massive to foliated granodiorite to granite
Metasedimentary rocks and derived gneisses
Metavolcanic and metasedimentary rocks

Location of Precambrian Geoscience Section field projects for 2003–2004. Numbers correspond to article numbers.

3. Precambrian Geoscience Section—Program and Project Overview

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GOAL AND RESPONSIBILITY OF THE PRECAMBRIAN GEOSCIENCE SECTION

The goal of the Precambrian Geoscience Section (PGS) is to improve the understanding of Precambrian geology and metallogeny of Ontario and to convey this knowledge to clients through multi-year, multidisciplinary geoscience studies that address critical geoscience problems in key geographic areas. These studies may be delivered as part of the PGS core bedrock mapping function or through collaborative partnerships.

PGS is responsible for

- mapping of Ontario's Precambrian bedrock and understanding of various mineral deposit settings
- regional gravity, magnetic and electromagnetic geophysical data and derivative products in support of the bedrock mapping program

PRECAMBRIAN GEOSCIENCE SECTION CORE FUNCTIONS

The program direction and strategic thrusts of PGS address the mission statement and core business of the Ministry of Northern Development and Mines (MNDM). Strategic thrusts (Table 3.1) are achieved through a variety of initiatives that are built upon one or more projects (Table 3.2). Therefore, project development, selection, planning and implementation are based on the strategic thrusts and initiatives in order to achieve alignment of individual projects with Ministry priorities.

The fundamental core functions of PGS projects are to:

1. provide geoscience maps, reports, data, technical talks and posters, new concepts and ideas and client consultations; and
2. provide regional airborne magnetic and electromagnetic geophysical data, derivative products, and concepts and ideas based on those geophysical data to support the bedrock mapping program.

The PGS supported 47 active projects during the 2004–2005 fiscal year including 31 active core projects (*see* Table 3.2) and 16 active collaborative project agreements, which include 9 projects with the Geological Survey of Canada (Table 3.3).

In 2004, the PGS produced 20 preliminary maps, 7 open file reports and 2 miscellaneous data releases (MRD). Airborne geophysical survey data were released in 10 publications during 2004. With the exception of the Shaw Dome area survey, all data were newly acquired through the Discover Abitibi and Lake Nipigon Region Geoscience initiatives. The total line-kilometres for the surveys published in 2004, to date, was 129 220 km (Rainsford and Muir, this volume). PGS staff presented approximately 30 technical talks and 49 posters at various geoscience forums and meetings throughout the year.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.3-1 to 3-18.

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Table 3.1. Strategic thrusts of the Precambrian Geoscience Section, 2004–2005.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces	Improve understanding of the tectonic and metallogenic evolution and mineral potential of the Superior, Grenville, and Southern provinces by integration of systematic bedrock mapping, mineral deposit studies, geological and geophysical interpretation and compilation at scales of 1:5000, 1:20 000, 1:50 000, 1:100 000, 1:250 000 and 1:2 000 000.	Provincial Initiatives	Provincial Resource Allocation: Undertake bedrock mapping and compilation augmented with mineral deposit data and geophysical interpretation of: • *non-frontier* areas and mining camps at scales of 1:20 000, 1:50 000 and 1:250 000 in the Abitibi greenstone belt and northeastern Ontario; conduct 1:20 000 and 1:50 000-scale bedrock mapping in the Michipicoten greenstone belt to document diamond-bearing Archean rocks. • *non-frontier* areas at 1:50 000-scale in the central Wabigoon Subprovince and the western Nipigon Embayment. • *non-frontier* areas in the River Valley area to update the 1:50 000 compilation map; complete 1:50 000-scale map of the Tomiko Domain which has Ni-Cu-PGE, gold and industrial mineral potential; 1:20 000-scale mapping in the Grimsthorpe Domain to study gold and diamond potential; begin 1:50 000-scale mapping in Porter–Vernon townships to study a number of metal commodities including Ni-Cu-PGE; complete geological compilation of the Georgian Bay area in the Grenville Province at 1:50 000-scale; paleomagnetic discrimination of Proterozoic mafic dikes in the Uchi and English River subprovinces in collaboration with the University of Toronto. • *frontier* areas at a scale of 1:20 000 in the Fort Hope greenstone belt.
		Abitibi Initiative	Abitibi Initiative: *Discover Abitibi*: In collaboration with Timmins Economic Development Corporation, academia and industry participate in the Discover Abitibi project through: • in-kind support by committing a portion of the PGS core bedrock mapping program to the Abitibi greenstone belt (Berger, Houlé, Trowell, Josey); • providing Senior Geoscientist (Ayer) and OGS Geophysicist (Rainsford) for participation on the Discover Abitibi Technical Committee; • supporting mapping school projects and participate in collaborative geoscience projects • providing a Senior Geoscientist to share science leadership and project co-ordination of the Greenstone Architecture Project which was a project award to Laurentian University (MERC).

Table 3.1. continued.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
1. (continued)		Proterozoic Initiative	Proterozoic Initiative: *a) Lake Nipigon Region Geoscience Initiative:* In partnership with Ontario Prospectors Association, industry, academia and other government surveys (i.e., USGS, Minnesota Survey, Geological Survey of Canada) participate by: • providing in-kind support by committing a portion of the PGS core bedrock mapping program to the Nipigon Region (Hart); • providing Senior Geoscientists (Easton) and OGS Geophysicist (Rainsford) for participation on the Science Advisory committee; • participating in collaborative geoscience projects with academia and other government surveys; • participating in planning meetings with OPA, Industry, First Nations, MNR, etc.; • participate in regional compilation of Mid-continent rift system with the USGS; • Delivering contract bedrock mapping to document the geology of Proterozoic and Archean rocks in the western Nipigon Embayment, under contract to Ontario Prospectors Association (MacDonald, Tremblay); • Developing 3D and 4D common earth model for the Lake Nipigon Region in collaboration with MIRARCO – Mining Innovation. b) *Sudbury ICDP project:* In partnership with Mineral Exploration Research Centre (MERC), Geological Survey of Canada, industry, and universities, contribute to the definition of geoscience needs and participate in the design of a geoscience proposal to ICDP to address science and technology gaps that encumber enhanced exploration of the Sudbury region.
		Metallogeny and Geology of Northwest Ontario	Metallogeny and Geology of Northwest Ontario: a) *Fort Hope Greenstone Belt:* Conduct bedrock mapping of both previously mapped and new areas along the Fort Hope greenstone belt at 1:20 000 and 1:50 000-scales. This follows the release of new geophysical and geochemical data sets previously released under the Operation Treasure Hunt Program. *b) Geology of the central Wabigoon Subprovince:* Conduct bedrock mapping at 1:50 000-scale and complete synoptic report and final 1:250 000-scale bedrock compilation map. *c) Geology of the Northern Superior Subprovince:* Complete 1:250 000-scale bedrock compilation map and final synoptic report.

Table 3.1. continued.

Strategic Thrust	**Thrust Objective**	**Initiatives To Achieve Thrust**	**Priority Action**
1. (continued)		Initiatives with GSC	Collaborative Initiatives with Geological Survey of Canada (GSC); *a) Western Superior NATMAP and Lithoprobe initiatives:* In partnership with Geological Survey of Canada, work to complete and publish the maps and reports for the Western Superior NATMAP and Lithoprobe initiatives to resolve the distribution of old and young crust and its metallogenic significance (Stone, Stott, Parker). *b) Far North Initiative (Exposed Sachigo and Precambrian basement project):* In partnership with Geological Survey of Canada, to stimulate exploration and support regional-scale bedrock interpretation of northern Ontario, interpret the geology of the exposed Sachigo and the Precambrian substrate to the James Bay and Hudson Bay lowlands (Stott). *c) Trans-Hudson–Superior Margin Metallotect Project:* In partnership with Geological Survey of Canada and DeBeers Canada Exploration Inc. conduct geochronology and isotopic work to discriminate between Archean tectonic domains across far northern Ontario.
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or deposits types currently of interest to the mineral exploration industry.	Improve the understanding of, and mineral potential for, rocks that may contain economic concentrations of: - diamonds; - rare-metal and petalite-bearing pegmatites; - Ni-Cu-PGE ; - Gold; - VMS-associated copper-zinc mineralization; and - metallic mineralization related to felsic magmatism	- Provincial-scale metallogenic inventory - Provincial-scale pegmatite mineralization - Provincial-scale diamond assessment - Documentation of magmatic nickel-copper-PGE metallogeny in Ontario	a) Document the distribution of, regional settings, and characteristics of: - Archean diamond-bearing rocks (Vaillancourt, Stone); - kimberlite indicator minerals and their distribution relative to major crustal structures in far northern Ontario and in northwestern Ontario (Stone); - fractionated pegmatites and related fertile granites that may host rare-metals and petalite in Ontario (Breaks); - gold mineralization and associated alteration (Beakhouse, Berger, Parker, Easton, Ayer); - mineralized, intermediate to felsic plutonic systems (Beakhouse); - evolved (FI to FIII-type) felsic metavolcanic rocks across the Superior Province (Hart); by conducting on-going mapping and office-based compilations and inventories supplemented by field work (e.g., sampling and localized bedrock mapping at various scales). b) Maintain geochronology database for Ontario (Easton).

Table 3.1. continued.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
3. Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-) formatting, organization and delivery of all available OGS and proprietary geophysical information; and provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.	Integrate regional geophysics into core business bedrock mapping projects.	Geophysics and Bedrock Mapping Integration Initiative	Provide on-going support of bedrock mapping and compilation projects.
			Develop new approaches, procedures and methodologies to integrate and establish geophysical component of bedrock mapping projects.
	Improve client awareness of, and access to, all OGS and proprietary geophysical data sets.		Assess and apply new technologies for processing, interpreting and presenting geophysical data (i.e. geophysical inversion and 3D visualization software).
			Maintain the Geophysical Atlas containing a graphical index of all available airborne geophysical survey information describing Ontario.
		Geophysics and Rock Properties Data Set Initiative.	Maintain an on-line repository (master archive) of all available airborne geophysical survey information, which will be used to seed all publications of geophysical data and which will be maintained by the OGS geophysicist.
			Continue the implementation and development of a rock properties database as part of OGS bedrock mapping projects i.e. recover rock density data; magnetic susceptibility data; specific gravity; establish data standards, storage format and plan.
			Acquire proprietary, multi-parameter, regional, airborne geophysical survey data.

Table 3.1. continued.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards and program management practices.	Implement human resource strategy by focussing on succession plans for critical positions and developing a PGS Learning Plan as required by Management Board Secretariat.	Strategic hiring and mentoring initiative to anticipate retirements of staff and loss of corporate and technical knowledge;	Address HR issues by: • Recruiting and filling the following staff vacancy: two Geoscientist-3 positions subject to exemption from present Government-imposed hiring freeze; • Developing and implementing staff technical and other training plans; • Maintaining the OGS Project Leader manual and Health and Safety manual; • Hire and train "strategically" to anticipate retirement and loss of corporate and technical knowledge; • Complete the competency model for the Geoscientist 3 field geologist function; • Participate in the OGS Branch review of the functions and responsibilities of the Geoscientist-2 and Geoscientist-3 field geologist functions.
	Complete Management Board Secretariat (MBS) mandated Program Review of geoscience program.	Support and Program Management Practices Initiative - Project and Results Management Initiative. - Methods Development and Data Standards Initiative.	Continue to implement and maintain project management tools and practices, including: • Project planning processes; • Track results and impacts of PGS program and provide leadership for impact of the OGS geoscience program; • Report on PGS performance measures; • Continue to collaborate with Corporate Services to complete a cross-business unit documentation of geoscience impact.
	Continue to implement project management and impact assessment practices.		Prepare field computers in advance of staff departure. Assess solutions for point-of-observation collection and processing of field data and begin developing a new process for collecting and digitizing field observations to streamline the workflow process for producing hard copy maps and digital data sets and creating a common archival format by: • Developing software and hardware solutions for field data collection and digitizing of geological observations; • fully integrating new solutions with current GIS data workflow; • working toward new data standards for PGS and facilitating production of hard copy maps & digital data; • purchasing software and hardware to be used for core program, pilot studies, methods development and standards projects.
	Provide staff with the Information Technology (IT) tools and operational manuals required to deliver the 2004 summer field projects.		Work with Information & Marketing Services and Business Solutions sections, and the rest of the OGS Branch to implement the OGS Branch information management and information technology plan by contributing staff resources as required. Apply drafting and GIS functions in support of the PGS mapping program by providing targeted staff with: • ArcGIS training for use in on-going projects; • Operational field computers and peripheral equipment; • Up-to-date digital mapping manual; • Up-to-date mapping project manual.

Table 3.1. continued.

Strategic Thrust	Thrust Objective	Initiatives To Achieve Thrust	Priority Action
5. Manage and maintain client, stakeholder, and First Nation relationships.	Contribute to awareness of external and internal clients and stakeholders and other ministries and governments, about the value of PGS Geoscience program, have a direct means to communicate with the PGS geoscience program, and manage PGS-related issues at as early a stage as possible. (now the role of the OGS Director)	External Committees. Internal Government committees. OGS Advisory Board and its Technical Committee and regional client association meetings. Maintain relationships and exchanging technical and administrative information with First Nation communities and organizations located in geographic areas where PGS has a geoscience program interest between now and 15 years into the future.	Client and stakeholder meetings: Represent MMD, OGS, and PGS on/at: - Committee of Provincial Geologists (function now part of OGS Director's office); - National Geological Surveys Committee (function now part of OGS Director's office); - APGO Council – Councillor for Northeastern Ontario - Board of Directors of Mineral Exploration Research Centre (Laurentian University) (function now part of OGS Director's office); - Board of the CAMIRO Exploration Division (function now part of OGS Director's office); - Chair OMET Management Board (function now part of OGS Director's office); - Commissioner, North American Commission on Stratigraphic Nomenclature; - International Continental Scientific Drilling Program; - regional client associations; - First Nation communities; - PGS Program-level discussions with other governments; - provide administrative support to the staff and managers of the Precambrian Geoscience Section and the Sedimentary Geoscience Section. OGS Advisory Board & OGS Technical Committee: Provide executive support. First Nation Communication Projects (function now part of OGS Director's office); Lead communication projects with Eabametoong First Nation, Neskanataga First Nation, Kasabonika First Nation, Marten Falls First Nation and Webequie First Nation. Other Ontario Government Ministries: Continue to maintain PGS program relationships with Ministry of Energy and the Ministry of Natural Resources (Peterborough Thunder Bay regional planning unit). Geological Survey of Canada: Continue to provide leadership and participate with other Canadian jurisdictions on the development of the Cooperative Geological Mapping Strategy (function now part of OGS Director's office).

Table 3.2. Precambrian Geoscience Section core projects, 2004–2005.

Initiative	**Project**	**Project Goal**	**Project Status**
Abitibi Initiative	Abitibi Compilation – 1:250 000 compilation	Complete 1:250 000-scale bedrock compilation of Abitibi greenstone belt.	On schedule for completion in 2004.
	Discover Abitibi	Participation in Technical Committee.	On-going.
	Regional mapping in the Matachewan area – Burt and Holmes townships	Map 6 townships and compile geology in Matachewan area.	1:20 000 maps published in 2004. Synoptic report and 1:50 000 compilation map in preparation.
	Bedrock mapping in the Timmins area – Carman and Langmuir townships	1:20 000-scale bedrock mapping; volcanology and economic potential of komatiitic rocks; gold potential.	Maps to be published in April 2005.
	Synthesis of Archean geology and diamond-bearing rocks in the Michipicoten greenstone belt	1:20 000-scale bedrock mapping of Menzies Township with 1:50 000-scale mapping in Musquash Township.	Bedrock mapping of Menzies Township completed. Map on schedule for publication in December 2004.
Proterozoic Initiative	Lake Nipigon Region Geoscience Initiative	Staff participation in Implementation and Science Advisory Committees.	On-going.
	Bedrock mapping of southern Nipigon Embayment	1:50 000-scale bedrock mapping over 2 years.	Second year of mapping completed. Map and report to be published in April 2005.
	River Valley bedrock compilation map	Update and add to current 1:50 000-scale compilation map.	Updated map to be published in April 2005.
	Geology and mineral potential of Porter–Vernon townships	Reconnaissance bedrock mapping and sampling in 2004.	Maps to be published in 2005–2006.
	Geology and mineral potential of Grimsthorpe area, Grenville Province	1:20 000-scale bedrock mapping of parts of Grimsthorpe, Tudor, Cashel and Limerick townships.	Map and report to be published in 2005–2006.
	Geology and mineral potential of eastern Tomiko terrane, Grenville Province	1:50 000-scale bedrock mapping of four 1:50 000 NTS sheets.	Map and report due to be published in 2005.
	Geological compilation of the Georgian Bay area, Grenville Province	Digitize and publish 1:50 000-scale maps by N. Culshaw.	Digitizing complete. Maps on schedule for publication in 2004.
Metallogeny and Geology of Northwest Ontario	Geology of the Wabigoon Area	Map Wabigoon–Dinorwic lakes area at 1:20 000- and 1:50 000-scales	Project on-hold for 2003.
	Geology of the Fort Hope greenstone belt	Map the Opikeigen Lake area at 1:20 000	Map to be published in 2005.
	Geology of the northern Superior Province	Prepare final synoptic report.	Compilation map and report to be published in 2004–2005.
	Geology of central Wabigoon Subprovince: geology and mineral potential of the Lac des Mille Lacs and Armistice Lake areas	1:50 000-scale bedrock mapping.	Bedrock mapping completed. Maps to be released in 2004 and 2005.
	Geology of central Wabigoon Subprovince: Bedrock compilation of the Atikokan area	1:250 000-scale compilation.	Map and report to be published in 2005–2006.

Table 3.2. continued.

Initiative	**Project**	**Project Goal**	**Project Status**
Provincial-scale Metallogenic Inventory Initiative	Distribution of potentially VMS-productive felsic metavolcanic rocks	Compile locations of FI, FII and FIII-type rhyolites across Ontario.	Project on-hold in 2004.
	Characteristics of mineralized intermediate to felsic plutonic systems	Gather/compile information on barren and mineralized felsic plutons across Ontario.	On-going compilation. Report to be published in April 2005.
	Update and maintain geochronology database	Maintain up-to-date geochronology database for Ontario.	On-going.
	Distribution and documentation of provincial-scale rare-element pegmatite mineralization	Document fertile peraluminous granites and related rare-element pegmatite mineralization in Ontario.	On-going documentation of pegmatites in Fort Hope greenstone belt. Results to be published in 2004–2005.
Provincial-scale Diamond Assessment	Study of diamond occurrences and kimberlite indicator minerals	Detailed petrographic study of Archean diamond-bearing rocks.	Report published in 2004.
Geophysics and Bedrock Mapping Integration Initiative	Fort Hope – New South Wales methodology	Apply NSW methodology to integrate geophysics with bedrock mapping.	Completed in 2004–2005.
	Geophysics integration with bedrock mapping projects	Integrate geophysics into the PGS bedrock mapping program.	On-going.
Geophysics and Rock Properties Dataset Initiative	Rock properties project	Collect and archive rock properties data.	On-going.
	Aur Resources Inc. legacy airborne geophysical surveys within the southern James Bay Lowlands	Digitally reprocess and prepare for publication.	8 surveys to be released in July 2005.
Support and Program Management Practices Initiative	Improving OGS Archives	Improve archives database and archiving processes.	On-going.
	PGS Learning Plan – Administrative Project	Develop and commit to learning plan for PGS.	On-going. Plan established for 2004–2005.
Strategic Hiring and Mentoring Initiative	Managing loss of staff, corporate and technical knowledge	Hire and train "strategically" to anticipate staff retirements.	On-going.
Project and Results Management Initiative	Impact analysis of PGS mapping program	Analyze impact of geoscience projects on economy of Ontario and mineral industry.	On-going.
Methods Development and Data Standards Initiative	Integrated solution for field data collection and processing	Establish new methods for digital collection of geological data in the field; development of data model for mapping projects.	On-going.
	Digital map standards throughout Ontario	Standardize digital map standards.	On-going.
	Attributed Maps (Smart Maps) Synoptic Mapping – Abitibi Subprovince & elsewhere	Release maps with database attached.	Project on hold in 2004.
External/internal committees; OGS Advisory Board; First Nations	On-going maintenance of relationships and exchange of information with clients, stakeholders and First Nations	Ensure external and internal clients and stakeholders are aware of the value of the PGS geoscience program.	On-going.

Table 3.3. Precambrian Geoscience Section collaborative projects, 2004–2005.

Initiative	**Project**	**Project Collaborator (s)**	**Project Progress**
Abitibi Initiative	Discover Abitibi – Greenstone Architecture Project	MERC–Laurentian University; University of Ottawa; University of Wisconsin–Oshkosh; Geological Survey of Canada; Consultants	Second year of field work completed.
	Discover Abitibi – Greenstone Architecture Project: Nickel Subproject	MERC–Laurentian University	Second year of field work completed. Report due in 2005.
Proterozoic Initiative	Midcontinent Rift Compilation	United States Geological Survey; Minnesota Geological Survey	On-going. Completion date in 2005.
	Lake Nipigon Region Geoscience Initiative	Ontario Prospectors Association; Lakehead University; Geological Survey of Canada; University of Alberta	On-going. Completion date in March 2005.
	Quantification of the benefits of virtual reality and common earth modelling for efficient data interpretation (applied to the Lake Nipigon bedrock mapping projects)	MIRARCO – Mining Innovation	Completion date in April 2005.
	Paleomagnetic discrimination of Proterozoic dike swarms in the English River and Uchi subprovinces	University of Toronto	Project started in 2004.
	Paleomagnetic discrimination of Proterozoic dike swarms east of Lake Nipigon	University of Toronto	Report to be published in April 2005.
Collaborative Projects with the GSC: Far North Initiative	Reprocessing and interpretation of ODM–GSC geophysics of exposed Archean in Sachigo Subprovince	Geological Survey of Canada	On-going, plan to complete in 2004 or 2005
	Reprocessing and interpretation of ODM–GSC geophysics of Proterozoic Substrate, James Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in 2004
	Reprocessing and interpretation of ODM–GSC geophysics of Archean Substrate, Hudson Bay Lowlands	Geological Survey of Canada	On-going, plan to complete in 2004

Table 3.3. continued.

Initiative	**Project**	**Project Collaborator (s)**	**Project Progress**
Collaborative Projects with the GSC: Trans-Hudson–Superior Margin Metallotect Project	Discrimination of Archean tectonic domains across northwestern Ontario, north of 52°	Geological Survey of Canada; DeBeers Canada Exploration Inc.	Commenced in 2003. Plan to complete in 2006.
Collaborative Projects with the Geological Survey of Canada (GSC): Western Superior NATMAP and Lithoprobe Initiatives	Structural/stratigraphic, metallogenic synthesis Red Lake greenstone belt	Geological Survey of Canada	1:50 000-scale map completed by GSC in 2004.
	Geology of east Sachigo Subprovince	Geological Survey of Canada	1:250 000-scale map completed by OGS in 2004.
	Geology of east Uchi Subprovince	Geological Survey of Canada	1:250 000-scale map completed by GSC in 2004.
	Regional metallogeny of northwest Superior Province	Geological Survey of Canada	Metallogenic maps to be completed by OGS in 2006.
Western Superior Lithoprobe Initiative	Western Superior Lithoprobe transects – reflection seismic transect routes	Geological Survey of Canada and various universities	On-going.

PROGRAM DIRECTION: STRATEGIC THRUSTS

Core Bedrock Mapping and Geophysics Program

The PGS Strategic thrusts (*see* Table 3.1) are derived from the Ministry business goals articulated in the MNDM business plan. The MNDM business plan is derived from Government's key priorities. At the beginning of its mandate, the Government established 5 key priorities:

- success for students;
- healthier Ontarians in a healthier Ontario;
- prosperity for people;
- safe, clean, livable communities; and
- working with citizens so government works for citizens.

The purpose of PGS Strategic thrusts is to focus skilled staff and resources in key geological areas or themes, over a period of 3 to 5 years. The PGS program is organized into 5 technical or administrative strategic thrusts.

1. Understand the geology and metallogeny of high mineral potential areas in the Superior, Southern and Grenville provinces.
2. Understand and inventory provincial-scale relationships, settings and descriptive data sets of commodities or mineral deposit types that are currently of interest to the mineral exploration industry (e.g., potential diamond-bearing rocks, gold mineralization, rare-element and/or petalite-bearing pegmatites, nickel-copper-platinum group element (PGE) mineralization and volcanogenic massive sulphide mineralization (VMS)) or may be of interest in the future.
3. Improve knowledge of, and access to, geophysical information by providing an effective and efficient information management system through the identification, recovery, (re-) formatting, organization and delivery of all available OGS and proprietary geophysical information; provide derivative geophysical products, concepts and ideas, based on those geophysical data, to support the bedrock mapping program.
4. Implement program support practices and instruments to address and refine the PGS core program, the human resource strategy, digital data standards, measurement of program results and impact and program management practices.
5. Develop and manage client and stakeholder relationships by: providing a liaison role, representation, or support on behalf of the PGS on client committees, regional client association meetings, inter-Ministry committees and formal or informal working groups; and committees or working groups associated with professional or learned associations. Maintaining relationships and exchanging technical and administrative information with First Nation communities and organizations located in geographic areas where PGS specifically has a geoscience program interest between the present and 15 years into the future.

These strategic thrusts are addressed through a series of initiatives, built upon one or more projects. The purpose of the strategic thrusts is to focus PGS staff and resources in key geological areas to address the priorities and needs of the initiative. In addition, PGS participates in several collaborative projects to complement existing PGS staff skills and capacity and to expand the amount of geoscience data available that describe Ontario. Collaborative projects are an important means to extend scarce government resources and to capitalize on resources and expertise available in other government geological surveys, universities or industry.

PROJECT PLANNING, MANAGEMENT, AND CONSULTATION PROCESS

PGS management and staff continued planning and project management processes and practices to deliver 47 geoscience projects conducted by core staff and in collaboration with partners. Information required to describe projects, monitor and adjust progress, and assess their impact on the minerals industry is collected and analyzed to assess achievement of program goals (e.g., Churchill and Fyon 1999; Churchill et al. 2000; Churchill, Fyon and Baker 2001).

To formulate and discuss project plans for summer of 2004 and to begin development of summer 2005 project plans, PGS staff were involved in several consultations with regional client associations:

- February 2004: Ontario Geological Survey Advisory Board
- March 2004: Southern Ontario Prospectors Association, Tweed
- April 2004: Porcupine Prospectors and Developers Association, Timmins
- May 2004: Sudbury Prospectors and Developers Association, Sudbury; the Sault and District Prospectors Association, Sault Ste. Marie; and the Northern Prospectors Association, Kirkland Lake
- June 2004: Northwestern Ontario Prospectors Association, Thunder Bay

NEW PROJECTS

The following new technical initiatives will be fully operational and will require resources of the PGS during the 2004–2005 fiscal year:

- PGS and MIRARCO – Mining Innovation are collaborating on a 3- and 4-dimensional common earth model to organize, visualize, and analyze geoscience data from the Lake Nipigon Region Geoscience Initiative using MIRARCO's Virtual Reality Laboratory.
- PGS staff are involved in an Ontario Geological Survey–Geological Survey of Canada Collaborative Project Agreement as part of the Trans-Hudson–Superior Margin Metallotect Project (Stott and Rayner, this volume).
- The Fort Hope bedrock mapping project began in 2004 as a result of First Nation communication and relationship-building projects with the Eabametoong First Nation (Deputy Minister and Chief signed a formal Cooperation Agreement in December 2002), Marten Falls First Nation, and Neskatanga First Nation.

ADD-ON PROGRAMS

PGS staff collaborated with other OGS staff to manage, deliver, or participate in 2 significant add-on geoscience programs:

- Discover Abitibi (PGS geoscientists conducting core business mapping in the Abitibi greenstone belt are integrated into this project as in-kind support);
- Lake Nipigon Region Geoscience Initiative (PGS is delivering the bedrock mapping component of this initiative and assisting in geoscience data integration under contract to and in collaboration with the Ontario Prospectors Association).

PRECAMBRIAN GEOSCIENCE SECTION INITIATIVES

PGS initiatives are based on geographic or functional groupings and are made up of 1) team initiatives (i.e., Abitibi Initiative) consisting of individual projects that are designed to meet an overall goal; 2) inter-jurisdictional team initiatives, such as Western Superior NATMAP, that consist of individual and joint Ontario Geological Survey (OGS) and Geological Survey of Canada (GSC) projects that are also designed to meet an overall goal or objective; and 3) individual, focussed projects. The major initiatives of the PGS are subdivided into 6 broad categories outlined below and in Table 3.2 and Table 3.3.

1. Initiatives that involve collaborative project agreements with the Geological Survey of Canada (GSC):
   - Western Superior NATMAP and Lithoprobe mainly focussed in north and northwest Ontario;
   - The Far North Initiative in the Sachigo Subprovince and the Hudson and James Bay lowlands;
   - The Trans-Hudson–Superior Margin Metallotect Project.
2. Initiatives involving provincial-scale metallogenic compilation and inventory studies:
   - Documentation of specific types of mineralization;
   - Inventories of various tectonic settings relevant to mineral exploration.
3. Initiatives based on geographic area:
   - Abitibi initiative;
   - Metallogeny and geology of northwest Ontario;
   - Proterozoic initiative.
4. Initiatives involving support of the PGS program:
   - Support to program management practices;
   - Project and results management;
   - Methods development and data standards;
   - Strategic hiring and mentoring.
5. Initiatives involving geophysical projects:
   - Geophysics and bedrock mapping integration initiative;
   - Geophysics and rock properties data set initiative.
6. Initiatives that develop and manage client, stakeholder and First Nation relationships:
   - External and internal committees;
   - Regional associations and participation at meetings of OGS Advisory Board and its Technical Committee;
   - Maintaining relationships and exchanging technical and administrative information with First Nation communities.

Collaborative Projects with the Geological Survey of Canada

Products from the Western Superior NATMAP initiative continued to be published in 2004. PGS completed and released the 1:250 000 East Sachigo Subprovince bedrock compilation map (Stone et al. 2004). PGS is also responsible for completing a series of 6 metallogenic compilation maps building upon the bedrock compilation maps. The GSC completed and released the 1:250 000 East Uchi Subprovince sheet (Sanborn-Barrie et al. 2004) and the 1:50 000 Red Lake sheet (Sanborn-Barrie, Skulski and Parker 2004). Interpretation of the Lithoprobe reflection seismic transect routes across the Western Superior Province continued in 2004 under the Western Superior Lithoprobe initiative.

G.M. Stott continued work on the geological interpretation of the Archean and Proterozoic substrate below the Phanerozoic cover of the James Bay and Hudson Bay lowlands and the exposed Archean in the Sachigo Subprovince as part of an Ontario Geological Survey–Geological Survey of Canada Collaborative Project Agreement. The interpretation is using reprocessed ODM–GSC airborne geophysical data and proprietary geophysical data purchased under the Operation Treasure Hunt initiative. The project will 1) compile geoscience data for the James Bay and Hudson Bay lowlands in order to provide an interpretation of bedrock features beneath the Phanerozoic cover; 2) produce 3, 1:500 000-scale geological maps in hardcopy and digital formats. The James Bay Lowlands sheet is scheduled for release in early 2005.

A project was initiated in 2004 to discriminate between Archean tectonic domains across northwestern Ontario as part of the lowland work described above and the Trans-Hudson–Superior Margin Metallotect Project with the GSC (Stott and Rayner, this volume). The project is a collaboration between the Ontario Geological Survey, DeBeers Canada Exploration Inc. and the Geological Survey of Canada. The project consists of sampling outcrops and diamond-drill core for geochronology and neodymium (Nd) and hafnium (Hf) isotopic characterization. The results will be used to assist in subdividing the most northern part of the Superior Province in Ontario into tectonic domains of contrasting age and tectonic development.

Provincial-Scale Metallogenic Compilation and Inventory Studies

The PGS continued a rare-element pegmatite characterization project to study rare-element mineralization. The purpose of this project is the preparation of a comprehensive field, chemical, mineralogical and geochronological database for fertile granites and associated rare-element pegmatites for the entire Superior Province of Ontario. Field work in 2004 focussed on the Fort Hope greenstone belt in the Uchi Subprovince in northwestern Ontario (Breaks and Tindle, this volume).

On-going, multi-year, province-scale projects that fall under the initiative to create inventories of various tectonic settings relevant to mineral exploration are 1) the documentation and distribution of FI-, FII- and FIII-type, potentially volcanogenic massive sulphide deposit (VMS)-productive felsic metavolcanic rocks; 2) characteristics of mineralized intermediate to felsic plutonic systems; and 3) update and maintain the geochronology database for Ontario.

Initiatives Based on Geographic Area

The Abitibi initiative includes 5 core business, multi-year, mapping projects (*see* Table 3.2) (Ayer, this volume), including the 1:250 000-scale compilation of the Abitibi greenstone belt as well as one collaborative project agreement (*see* Table 3.3).

J.A. Ayer is the PGS representative on the Discover Abitibi Technical Committee. The Discover Abitibi Initiative is a community based and directed program designed to stimulate exploration for, and eventual development of, mineral deposits within the Abitibi greenstone belt of northeastern Ontario. The program will be achieved through the co-operation and collaboration between Federal, Provincial and Municipal governments and private-sector partners. The Discover Abitibi Initiative includes several new geophysical surveys and the continuation of new bedrock mapping and metallogenic research under the Greenstone Architecture Project (*see* Ayer et al., this volume). This project was awarded to the Mineral Exploration and Research Centre (MERC)–Laurentian University and involves an international multi-disciplinary science team. J.A. Ayer shares science leadership and project co-ordination with MERC–Laurentian University staff for the Greenstone Architecture Project. The major goal of the project is to obtain an improved understanding of the controls on base metal and gold mineralization in a number of key areas with good economic potential in northeastern Ontario. Several subprojects in the Greenstone Architecture Project are described in detail in a separate Discover Abitibi section of this volume (*see* Articles 37 to 46).

Bedrock mapping at 1:20 000- and 1:50 000-scale continued in the Michipicoten greenstone belt at Wawa (Vaillancourt et al., this volume). The purpose of the project is to document the geological environment of diamond-bearing Archean breccias and lamprophyres.

The geology and metallogeny of the northwest Ontario initiative currently includes 5 core projects:

- geological mapping in the Dryden–Wabigoon area, which was suspended for 2004;
- bedrock mapping in the Lac des Mille Lacs and Armistice Lake areas of the central Wabigoon Subprovince (Stone, this volume);
- a 1:250 000-scale compilation of the Atikokan area resulting from 5 years of bedrock mapping in the central Wabigoon Subprovince;
- 1:20 000-scale bedrock mapping in the Opikeigen Lake area of the Fort Hope greenstone belt (Hall, this volume); and
- completion of the 1:250 000-scale bedrock compilation map and synoptic report for the northern Superior Province.

The Proterozoic initiative includes several projects such as

- Geological compilation (1:50 000-scale) of the Georgian Bay area, Grenville Province;
- 1:50 000-scale reconnaissance study of the geology and mineral potential of the eastern Tomiko terrane, Grenville Province;
- 1:20 000-scale bedrock mapping in the Grimsthorpe area, Grenville Province (Easton, this volume);
- 1:20 000-scale bedrock mapping in Porter and Vernon townships, west of Sudbury (Easton, this volume);
- Updating of the 1:50 000-scale River Valley bedrock compilation map;
- PGS and MIRARCO – Mining Innovation collaboration on a 3- and 4-dimensional common earth model for the western Lake Nipigon Embayment using MIRARCO's Virtual Reality Laboratory;
- Paleomagnetic discrimination of Proterozoic dike swarms in the English River and Uchi subprovinces, which is an Ontario Geological Survey–University of Toronto Collaborative Project Agreement (Halls and Stott, this volume); and
- A continuation of a compilation of the geology of the Mid-Continent Rift conducted in collaboration with the United States Geological Survey and the Minnesota Geological Survey.

The Proterozoic initiative also includes the Lake Nipigon Region Geoscience Initiative (LNRGI). LNRGI is operated by the Ontario Prospectors Association (OPA) and funded through an agreement with the Northern Ontario Heritage Fund Corporation (Rayner, this volume). LNRGI involves partnerships with the private sector, Lakehead University, Geological Survey of Canada and several communities in the Lake Nipigon area. The aim of LNRGI is to attract mineral industry investment to the Lake Nipigon area through bedrock mapping, airborne and ground geophysical surveys and targeted surficial geochemical and geochronological studies.

This was the final year of 1:50 000-scale bedrock mapping of the western Nipigon Embayment (*see* Figure 43.1 in Rayner, this volume). The southern part of the Nipigon Embayment was mapped by the PGS as part of its commitment of in-kind support to the LNRGI (Hart and Whaley, this volume). Mapping of the northern and central parts of the western Nipigon Embayment is conducted under a contract agreement between the Ontario Geological Survey and the OPA for the LNRGI (MacDonald, Tremblay and Easton, this volume). These mapping projects include interpretation of igneous petrogenesis; stratigraphic analysis; construction of geological cross-sections; collection of rock properties data (i.e., magnetic susceptibility, specific gravity); integration of newly acquired airborne magnetic and gamma-ray geophysical data as well as ground geophysical gravity data; newly acquired geochronological data; and re-logging of existing diamond-drill core. This work is conducted in collaboration with staff and MSc students at Lakehead University. LNRGI will generate new geoscience data and ideas for the Lake Nipigon area to understand the geological and metallogenic evolution of the region and to stimulate mineral exploration for a variety of mineral deposit types including magmatic nickel-copper-platinum group element mineralization and possible Olympic Dam-type iron-copper-uranium-gold mineralization. Several LNRGI projects are described in detail in a separate LNRGI section of this volume (*see* Articles 47 to 53).

Initiatives Involving Geophysical Projects

Several geophysical projects and activities are described in detail in Rainsford and Muir (this volume). Integration of geophysics into the bedrock mapping projects continues with many geoscientists routinely using hand-held magnetic susceptibility meters during mapping as well as a variety of geophysical data and derived products for interpretation.

Modelling of magnetic data has been facilitated by the use of magnetic susceptibility data now routinely collected as part of the bedrock mapping program. Smooth model inversion software and other simpler and faster modelling tools have been used to provide insight into specific mapping problems.

Technical support is provided to the Discover Abitibi and LNRGI initiatives as part of in-kind support by the PGS. On-going assistance with the publication of digital data sets, from recently flown airborne geophysical surveys, and the integration of geophysical data into the Greenstone Architecture Project is provided to Discover Abitibi. Participation in LNRGI includes on-going assistance with the publication of digital data sets, development of a geophysical inversion model using LNRGI geophysical data and the integration of geophysical data into the LNRGI bedrock mapping projects. The geophysics is augmented with magnetic susceptibility and density data collected as part of the bedrock mapping.

Basic geophysical training for use by prospectors was delivered at the Northwest Ontario Mines and Minerals Symposium in April 2004. Other activities have included the acquisition of archived airborne geophysical data for eventual public release.

INTER-JURISDICTIONAL AND COMMITTEE REPRESENTATION

PGS staff represented the Ontario Geological Survey on several inter-jurisdictional committees, internal committees and associations during the 2004 to 2005 fiscal year, including

1. Committee of Provincial Geologists (now part of the OGS Director's function)
2. National Geological Surveys Committee (now part of the OGS Director's function)
3. Board of Directors – Mineral Exploration Research Centre (now part of the OGS Director's function)
4. Chair – OMET Management Board (now part of the OGS Director's function)
5. Commissioner, North American Commission on Stratigraphic Nomenclature
6. APGO Councillor for Northeastern Ontario
7. International Continental Scientific Drilling Program
8. Discover Abitibi Technical Committee
9. MNDM Health & Safety Committee
10. Ontario Association of Remote Sensing
11. MSc committees at Laurentian University
12. Lake Nipigon Region Geoscience Initiative

STAFFING CHANGES IN THE PRECAMBRIAN GEOSCIENCE SECTION

J.A. Fyon accepted the position of Director, Ontario Geological Survey in July 2004. As a result, J.R. Parker is currently acting as Senior Manager for the PGS. Several staff, as part of a management training and development opportunity, will be backfilling the position of Manager, Bedrock Mapping and Geophysics.

J. Chartrand joined the PGS in November 2003 as the Drafter for the section. E. Tremblay accepted a contract position with the PGS in March 2004 to assist in the Lake Nipigon bedrock mapping project as part of the Lake Nipigon Region Geoscience Initiative.

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4. The Abitibi Greenstone Belt: A Program Update

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INTRODUCTION

The Precambrian Geoscience Section program in the Abitibi greenstone belt is designed to facilitate exploration by providing current geological mapping in areas of high mineral potential at a variety of map scales. Parker (this volume) lists current core projects.

CURRENT PROJECTS

To date, the Abitibi compilation project has produced hard-copy and digital versions of the Timmins, Lake Abitibi, Kirkland Lake, Swayze and Matachewan map areas at a scale of 1:100 000 (Ayer and Trowell 1998; Ayer, Trowell and Berger 1999; Ayer and Trowell 2000; Ayer and Trowell 2002; Ayer, Trowell et al. 2003). A compilation sheet at a scale of 1:250 000 covering all of the above areas is planned for release as a MRD (Miscellaneous Release—Data) in December of this year and as hard-copy products in 2005. The compilation, in conjunction with new geochronological and lithogeochemical sampling, will enable further review and refinement of the assemblages and the timing of mineralization (Ayer, Amelin et al. 2002; Ayer, Ketchum and Trowell 2002; Ayer, Barr et al. 2003); establishment of a more formalized stratigraphy; and the erection of new metallogenic and geodynamic models for the evolution of the Abitibi greenstone belt. In addition, a number of ongoing mapping and research projects at a variety of scales (discussed below) are designed to focus on areas where we currently have an inadequate understanding of the relationships between mineralization and geology, and provide new data for the compilation project.

The author is the Ontario Geological Survey's representative on the Technical Committee of the Discover Abitibi Initiative and is the co-ordinator for the Greenstone Architecture Project (described below). The Discover Abitibi Initiative is a community-based and directed program designed to stimulate exploration for, and eventual development of, mineral deposits within the Abitibi greenstone belt of northeastern Ontario. The program is being achieved through the co-operation and collaboration between Federal, Provincial and Municipal governments and private-sector partners. A number of new geophysical surveys and other projects are currently being undertaken (see www.discoverabitibi.com). The Discover Abitibi Initiative funding has resulted in a new mapping and metallogenic research project identified as the Greenstone Architecture Project (*see* Ayer, Thurston et al. 2003; Ayer, Thurston et al., this volume). This project is focussed on an improved understanding of the controls on base metal and gold mineralization in a number of key areas with good economic mineral potential. The subprojects are described in detail in a separate Discover Abitibi section of this volume (*see* Articles 37 to 46).

M.G. Houlé conducted 1:20 000-scale bedrock mapping for the Precambrian Geoscience Section in Carman and Langmuir townships (Houlé and Guilmette, this volume) as part of an ongoing project to update geological mapping in the Timmins mining camp. This project follows bedrock mapping of

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.4-1 to 4-3.

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Deloro, Shaw, Eldorado and Adams townships (Hall and Houlé 2003). The 4 major goals of this project are to 1) clarify lithologic uncertainties and to refine lithologic and assemblage boundaries; 2) to better understand the stratigraphic and structural nature of the Shaw Dome; 3) to evaluate the mineral potential of the area; and 4) to study the ultramafic metavolcanic or intrusive rocks. Numerous gold occurrences in the Shaw Dome demonstrate that gold mineralization is present south of the Porcupine–Destor deformation zone. However, relatively little gold exploration has been carried out in this part of the Timmins camp for the last 20 years. A close spatial relationship between extrusive or intrusive ultramafic rocks and sulphide-bearing iron formation occur extensively along the margins of the Shaw Dome. The combination of abundant olivine cumulate (i.e., high magma flux) and its proximity to sulphide–bearing iron formation (i.e., a sulphur source) results in increased potential to discover economic komatiite-associated nickel-copper-platinum group elements (PGE) deposits as is indicated by the presence of a number of past-producing nickel-copper mines in the map area.

A multi-year project along Highway 66 from Swastika to Matachewan has resulted in a number of townships being mapped at 1:20 000-scale over the last 3 summers (*see* Berger and Leblanc 2002, Pigeon and Berger 2003). The close proximity of the map area to the Kirkland Lake and Matachewan gold camps emphasises the need to advance our knowledge of the geology of this area. This summer's mapping in Burt, Holmes and parts of Flavelle and Gross townships (Berger, this volume) has indicated that shear zone-hosted gold mineralization is associated with the Galer Lake and Kinkaid faults, the Larder–Cadillac deformation zone and associated subparallel shear zones. Disseminated pyrite is most closely associated with the gold mineralization but associated hydrothermal alteration is dependent upon the host rock. Porphyry-style copper-gold mineralization is associated with the Cairo syenite stock and syenite dikes at Galer Lake.

An increase in the number and significance of diamond discoveries in Archean rocks of the Michipicoten greenstone belt of the Wawa Subprovince in the last few years has resulted in rising interest in diamond exploration in the Wawa area. Bedrock mapping, at a scale of 1:20 000, was started in Menzies Township in 2003 (Vaillancourt, Wilson and Dessureau 2003). Part of this summer was spent completing and revising the mapping of Menzies Township with the goal of publishing a map at 1:20 000-scale in December of 2004. The remainder of the summer was used to map the southwestern portion of Musquash Township and to start reconnaissance work in Lalibert and Leclaire townships. Vaillancourt et al. (this volume) reports on the results of the new mapping and on new geochronological data that indicates the diamondiferous heterolithic breccias are diatremes (typically with the highest diamond content) and are coeval with the diamondiferous lamprophyre dikes, both being about 20 million years younger than the metavolcanic host rocks of the Catfish assemblage (circa 2700 Ma).

CONCLUSIONS

In summary, many exciting new advances in our understanding of the geology of the Abitibi greenstone belt are being made. The following reports in this volume demonstrate the merits of a diverse, but balanced, approach to Abitibi Subprovince geology using the traditional strengths of Precambrian Geoscience Section bedrock mapping, the comprehensive understanding of the ore deposits by the mining companies working in the area and the research skills of university geology departments. The Discover Abitibi Initiative has provided a unique opportunity to fund new innovative mapping-based research on key metallogenic problems in the Abitibi greenstone belt using non-core OGS, Federal, Provincial and Industry funding. This balanced approach to mapping and research embraces projects at a wide variety of scales and methodologies that are required for the range of problems that exist. The projects range from belt-wide compilation, to township-scale bedrock mapping to extremely detailed outcrop-scale mapping. The program is also focussed on the economically important parts of the belt. We feel our integrated approach to applied research through collaboration with our mining company clients and the earth science departments of a number of universities is needed to advance our understanding of the geology and its relationship to mineral deposits in this geologically complex, but highly prospective, part of the province. We also feel confident that the maps, reports and theses resulting from this comprehensive program will provide many new ideas and concepts that are, and that will continue to be, directly applicable to exploration for new mineral deposits.

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5. Project Unit 00-010. Geology of Burt–Holmes Area, District of Timiskaming

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INTRODUCTION

Burt, Holmes and parts of Flavelle and Gross townships were mapped at 1:20 000 scale by the author over the last 3 summers as part of a multi-year project along Highway 66 from Swastika to Matachewan (*see* Berger 2001; Berger and Leblanc 2002; Pigeon and Berger 2003, 2004; Figure 5.1). The area covered approximately 200 km^2 and was mapped to improve the geological database and provide impetus for mineral exploration. Previous mapping by Moore (1966a, 1966b) identified the major rock units and structures; however, the application of geochemistry and use of modern airborne geophysical techniques has permitted better resolution of the structural geology and geochemical discrimination of the geological units. This information was used to gain insight into the nature and controls on mineralization in the map area.

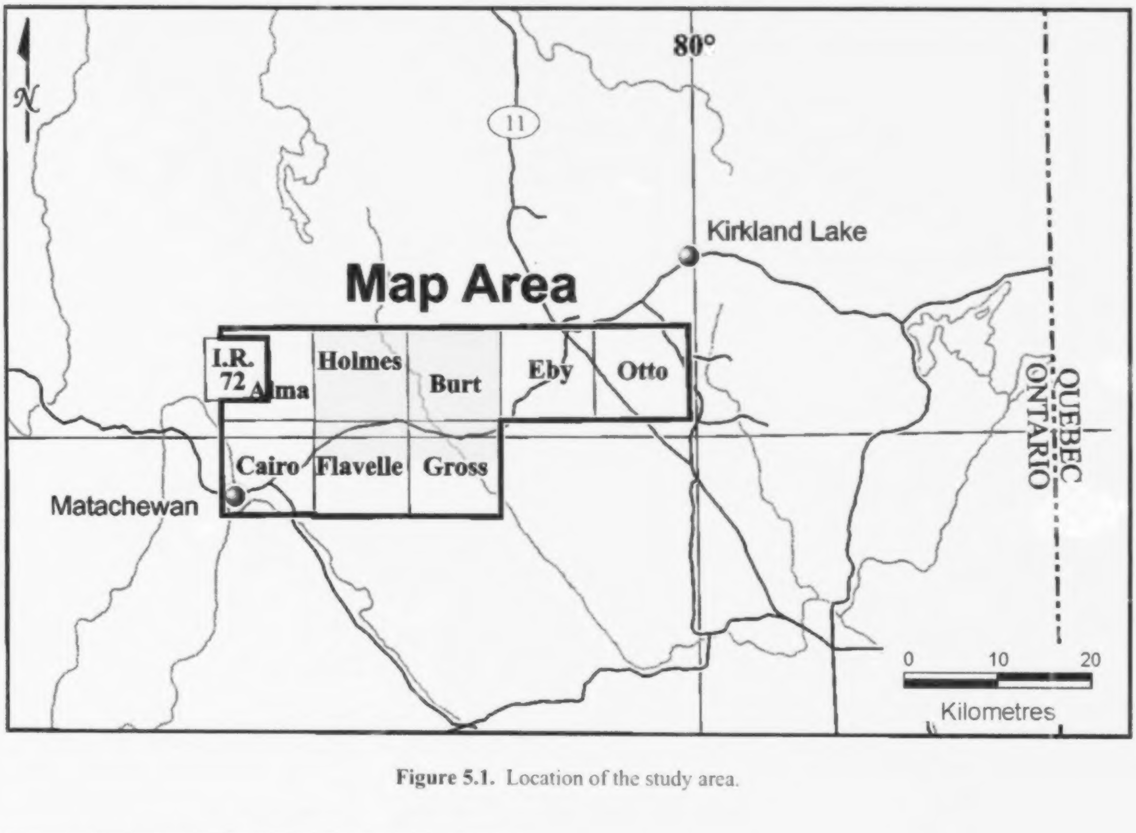

Figure 5.1. Location of the study area.

Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.5-1 to 5-9.

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GENERAL GEOLOGY

The map area is underlain by Neoarchean mafic, intermediate and felsic metavolcanic rocks, related intrusive rocks, Neoarchean clastic and chemical metasedimentary rocks and alkalic metavolcanic rocks (Figure 5.2). These rocks are intruded by Archean calc-alkalic intermediate and felsic plutonic rocks, mafic, intermediate and felsic alkalic rocks and Paleoproterozoic diabase dikes of the Matachewan swarm. Clastic sedimentary rocks correlated with the Proterozoic Gowganda Formation of the Cobalt Group of the Huronian Supergroup unconformably overlie the Archean rocks. The map area covers part of the western extension of the Larder Lake–Cadillac deformation zone, a regional-scale structure spatially associated with gold mineralization. The mapping helped to delineate and characterize the many structural components of the deformation zone and related structures.

Neoarchean Rocks

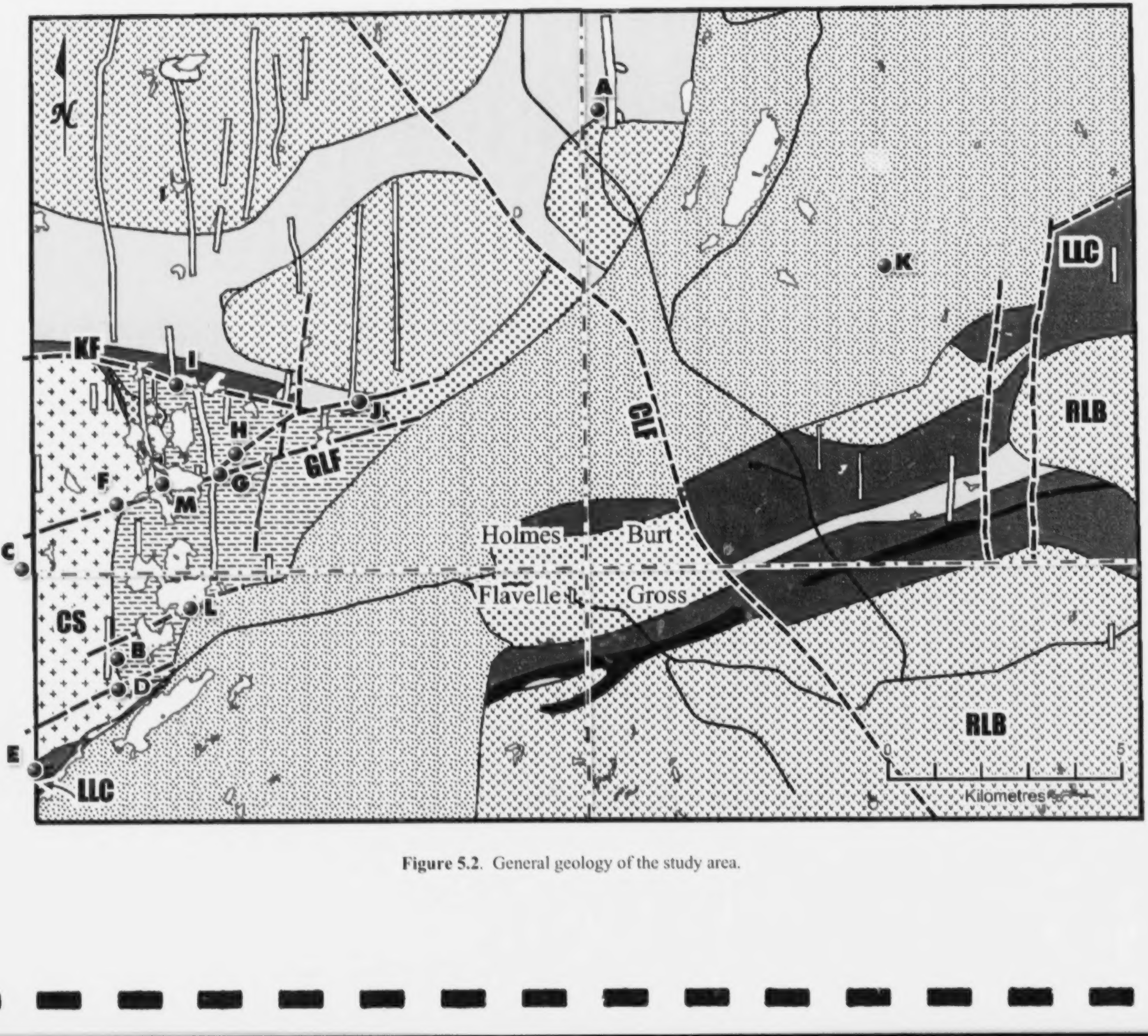
Mafic metavolcanic rocks form a northeast-striking unit that underlies south Burt and north Flavelle townships (*see* Figure 5.2). These rocks are metamorphosed and extensively recrystallized to amphibolite, mafic gneiss and schist. Massive flows are most common, but pillow and flow breccia textures are locally observed. Intermediate and felsic metavolcanic tuff and lapilli tuff are interbedded with the mafic metavolcanic flows but rarely form mappable units. The mafic metavolcanic rocks are contiguous to the east with mafic metavolcanic rocks in Eby Township (*see* Pigeon and Berger 2003) and are covered by Proterozoic metasedimentary rocks of the Gowganda Formation to the west.

Intermediate metavolcanic rocks form mappable units in two parts of the map area. A unit up to 500 m wide of strongly recrystallized tuff, lapilli tuff and schist underlies the south part of Burt Township and extends discontinuously into Flavelle Township. These rocks are similar to intermediate metavolcanic rocks interbedded with the mafic units described above. Primary features are largely destroyed by high-grade metamorphism and strong recrystallization, but bedding and clast gradation are locally preserved.

Intermediate tuff breccia, lapilli tuff, tuff and rare pillowed and massive flows underlie the northwest part of the map area. These rocks are characterized by abundant white, anhedral to euhedral plagioclase phenocrysts and porphyroblasts up to 7 mm in size. The rocks are contiguous with calc-alkalic, intermediate metavolcanic pyroclastic units and flows west of the map area (Kresz 1993). The large volume of pyroclastic material, rare preservation of gas cavities and abundance of amygdules in flows suggest a shallow water depositional environment for these rocks.

Felsic metavolcanic rocks are rare and commonly restricted to narrow units intercalated with intermediate metavolcanic rocks and with clastic metasedimentary rocks in Flavelle and Burt townships.

Clastic and chemical metasedimentary rocks form a unit up to 250 m wide that can be traced in outcrop and by airborne magnetic geophysical surveys through Burt and north Flavelle townships. The unit is dominated by thinly bedded to laminated chert and magnetite iron formation; however, wacke, schist, derived amphibolite and gneiss are locally abundant. Although this unit is intruded by granodiorite of the Round Lake batholith, it can be traced through Eby and Otto townships and is likely the same unit that formed the Adams iron deposit approximately 25 km east of the map area (Pigeon and Berger 2003), and if so, it is correlated with the Tisdale assemblage having an age of ca. 2710 Ma in the vicinity of the Adams mine (Ayer et al. 2002).


N
A
K
LLC
KF
I
J
H
GLF
G
F
M
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CLF
Holmes
Burt
Flavelle L.
Gross
RLB
CS
L
B
D
E
LLC
RLB
0
5
Kilometres

Figure 5.2. General geology of the study area.

Abbreviations:

CS Cairo stock
RLB Round Lake batholith
LLC - Larder Lake Cadillac deformation zone
GLF Galer Lake fault
KF Kinkaid fault
CLF Cross Lake fault

Mineral Occurrences

A Ag, Au, py
B McChesney Showing Au
C Brookbank Showing - Au
D Au, cp
E Cu, Au
F Au, barite
G Au, py
H Au
I Au
J Au
K Au
L Au
M cp, py

▨ *Gowganda Formation clastic metasedimentary rocks*
▨ *Calc alkalic intermediate and felsic intrusive rocks*
▨ *Alkalic intrusive rocks*
▨ *Mafic intrusive rocks*
▤ *Alkalic metavolcanic and sub-plutonic rocks*
▨ *Timiskaming clastic metasedimentary rocks*
■ *Clastic and chemical metasedimentary rocks*
□ *Intermediate metavolcanic rocks*
■ *Mafic metavolcanic rocks*
╌ *Fault*
● *Mineral Occurrence*

Figure 5.2, continued. Legend for general geology map. Abbreviations: Ag, silver; Au, gold; cp, chalcopyrite; Cu, copper; py, pyrite.

Clast-supported pebble and boulder conglomerate exposed along Highway 66 in Flavelle Township, and north of Galer Lake in Holmes Township is correlated with the Timiskaming assemblage and is interbedded with wacke, siltstone, schist and intermediate alkalic metavolcanic rocks. Syenite boulders similar to the main phase of the Cairo stock are most abundant in the conglomerate; chert, sulphide clasts, wacke and aphanitic felsic clasts are subordinate.

Alkalic to subalkalic metavolcanic and subplutonic rocks are closely associated with the Timiskaming assemblage metasedimentary rocks and are located in central and southern Holmes Township. Intermediate to felsic epiclastic tuff breccia and lapilli tuff are gradational with pyroclastic and trachytic flows centred east of Galer Lake and are, in turn, gradational with massive trachyte interpreted by the author to represent a subvolcanic lava dome or hypabyssal pluton. The lava dome, previously referred to as the "Dixon Lake syenite" (cf. Moore 1966a, 1966b) is fine- to medium-grained, amphibole and feldspar porphyritic and locally displays monolithic breccia interpreted to have formed by hydraulic fracturing. The gradational contacts with metavolcanic rocks of similar composition and the absence of an obvious contact metamorphic aureole are additional evidence that the "Dixon Lake syenite" is a high level pluton that intruded its own volcanic pile.

Numerous mafic, intermediate and felsic calc-alkalic to alkalic plutons intruded the Neoarchean supracrustal rocks. A poorly exposed gabbro intrusion underlies the south part of the map area and includes melagabbro, gabbro, leucogabbro and pegmatitic phases. The intrusion appears to be part of the supracrustal assemblages and is similar to a gabbroic intrusion in Eby Township (Pigeon and Berger 2003, 2004).

Part of the Round Lake batholith underlies the southeast part of the map area (cf. Chown, Harrap and Moukhsil 2002). This is a multi-phase intrusion that is composed of banded and injection gneiss, metatexite, diatexite and a late phase granodiorite. The medium- to coarse-grained, massive granodiorite has abrupt contacts with, and has imparted a contact metamorphic aureole on to, the supracrustal rocks and older phases of the Round Lake batholith. The gneissic and migmatitic phases of the batholith display a progression from dioritic agmatite and amphibolite adjacent to the supracrustal contact to in situ metatexite to tonalitic diatexite injected with aplitic and tonalitic stringers and dikes toward the centre of the intrusion. This progression suggests that development of the batholith involved assimilation of older supracrustal rocks that are no longer recognized in the map area. A U/Pb zircon age of 2742±2 Ma from early gneissic tonalite (J.A. Ayer, Ontario Geological Survey, personal communication, 2003) confirms that an older supracrustal assemblage, possibly correlative with the Pacaud assemblage, was intruded in the batholith.

White weathering, medium-grained tonalite to granodiorite in east-central Burt Township is separated from the main part of the Round Lake batholith by a narrow septum of amphibolitized mafic metavolcanic rocks. This massive to weakly foliated intrusion is, in part, unconformably overlain by the Paleoproterozoic Gowganda Formation; however, airborne magnetic geophysical data indicate that this intrusion does not extend north of the Larder Lake–Cadillac deformation zone (OGS 2000).

The northwest part of the map area is underlain by amphibole-bearing granodiorite and quartz monzonite that is part of a much larger calc-alkalic intrusion that extends north of Holmes Township. Phases of this intrusion are medium-grained, massive to weakly foliated with abrupt contacts with the supracrustal rocks.

The Cairo stock underlies the west part of Holmes and northwest part of Flavelle townships. This stock is composed predominantly of pink to red weathering, medium-grained, equigranular syenite with minor quartz syenite phase. Amphibole and biotite are common mafic minerals, magnetite, apatite and titanite are the most common accessory minerals. The stock extends to the west and has been described by Berger and Leblanc (2002) and Leblanc and Berger (2003).

An intermediate to felsic intrusion in the central part of Holmes Township and west part of Burt Township appears to be transitional from alkalic to calc-alkalic composition based on field observations and rock types. The core of the intrusion is composed of quartz monzonite and granodiorite that are gradational with marginal phases composed of diorite, monzonite, melasyenite and gabbro. The marginal phases locally display extensive hematization, assimilation of the host country rock, abundant networks of feldspar and epidote veining and vari-textured rocks from aplite to pegmatite. This "hybridization" of rock types makes it difficult to map out well-defined contacts between the intrusion and the supracrustal rocks.

Proterozoic Rocks

Numerous diabase dikes correlated with the Paleoproterozoic Matachewan swarm intrude all Archean rocks in the map area (Osmani 1991). Two types of dikes are recognized: plagioclase phyric dikes with phenocryst abundance greater than 1% and plagioclase aphyric dikes. Both types display moderate to high magnetic susceptibility.

Clastic metasedimentary rocks correlated with the Gowganda Formation of the Cobalt Group of the Proterozoic Huronian Supergroup unconformably overlie all Archean rocks and occupy the central portion of the map area. Matrix-supported boulder conglomerate is most common and clasts vary from 1 to 70 cm in diameter and from less than 1% to greater than 70% in abundance. Pink granitoid clasts are most abundant but mafic metavolcanic, tonalitic, gneissic, quartz vein and gabbroic clasts were also observed. Isolated "dropstones" in siltstone were observed in several locations and have been included under the "conglomerate" designation on the map (in preparation). Sandstone, siltstone, wacke and argillite are common and tend to occur more frequently in the central and eastern parts of the Formation in the map area. These rocks are thinly to thickly bedded and generally less deformed than Neoarchean metasedimentary rocks.

STRUCTURE AND METAMORPHISM

Neoarchean, Proterozoic and probably Paleozoic deformational events have affected the rocks in the map area (Lovell and Caine 1970).

Neoarchean deformation is characterized by multiple folding, shearing and faulting. The Larder Lake–Cadillac deformation zone (LLC, *see* Figure 5.2) is a regional northeast-striking shear zone that transects the map area. Much of the deformation zone is covered by the Gowganda Formation and can be traced only with airborne magnetic geophysical data (OGS 2000); however, the deformation zone is exposed intermittently in east Burt and northwest Flavelle townships. Dextral movement with shallow west-plunging extension lineations indicate that late movement was largely strike-slip on the Larder Lake–Cadillac deformation zone. A number of subparallel shear zones occur north of the Larder Lake–Cadillac deformation zone; among them the Galer Lake and Kinkaid faults also display late dextral strike-slip movement. Moderate southwest-plunging lineations on the Galer Lake fault (GLF, *see* Figure 5.2) indicate a component of north-side-up vertical movement. On the Kinkaid fault (KF, *see* Figure 5.2) foliation planes associated with the dextral movement fold and transpose and earlier foliation indicating that at least two deformation events affected the rocks in this area. Gold mineralization is associated with many of these shear zones and each structure represents an attractive exploration target.

Paleoproterozoic deformation is recorded in outcrops of the Gowganda Formation where they overlie the trace of the Larder Lake–Cadillac deformation zone. Finely spaced cleavage planes parallel to the strike of the underlying deformation zone were observed in outcrops of argillite in Holmes Township.

Powell and Hodgson (1992) concluded that these features indicated that dextral strike-slip reactivation of northeast-striking Archean structures had occurred possibly related to development of the Kapuskasing Structural Zone or during the Grenville Orogeny. Numerous north- and north-northwest-striking faults occur in the area and some penetrate into the Gowganda Formation. These features are also likely to be Neoarchean structures reactivated during the Proterozoic.

Paleozoic deformation during the Timiskaming Structural Zone rifting event is represented by the northwest-striking Cross Lake fault (CLF, *see* Figure 5.2) (Lovell and Caine 1970). The Cross Lake fault has pronounced airborne magnetic and gravity anomalies (OGS 2000) associated with its trace and for this reason the author suspects that the fault is a Neoarchean structure that was reactivated several times over its long history. Airborne magnetic geophysical anomalies correlated with Neoarchean units are attenuated by the overlying Gowganda Formation (OGS 2000). The attenuation is more pronounced east of the Cross Lake fault which leads the author to infer that the Gowganda Formation is thicker in this area. This implies that the Cross Lake fault has had significant east-side-down displacement.

Metamorphism is quite variable in the Neoarchean rocks across the map area. Low-grade greenschist metamorphism occurs in east Burt Township and locally in Flavelle Township and is characterized by epidote, chlorite and white mica mineral assemblages in mafic and intermediate metavolcanic rocks. In other parts of the map area, these units more typically contain secondary amphibole, epidote and abundant feldspar with little or no chlorite and white mica. The rocks are strongly recrystallized and locally gneissic. Rare aluminosilicate minerals and garnet are present. These features are indicative of upper greenschist- to amphibolite-grade metamorphism and are most commonly developed within 500 m of the various plutonic rocks in the map area.

The alkalic metavolcanic and subplutonic rocks commonly have a metamorphic mineral assemblage of epidote and biotite with subordinate amounts of chlorite, white mica and rare secondary amphibole. Iron carbonate, white mica and chlorite are common in the many shear zones that transect these rocks and these minerals are most compatible with alteration and greenschist-grade metamorphism.

The widespread occurrence of epidote, chlorite, white mica and rare biotite in sandstone and argillite indicate that the Gowganda Formation was subjected to low grade regional metamorphism rather than localized contact metamorphism adjacent to Proterozoic dikes.

RECOMMENDATIONS FOR EXPLORATION

The feldspar phyric intermediate metavolcanic rocks in the north part of the map area have the potential to host base and precious metals. A mineral prospect in north Burt Township ("A", *see* Figure 5.2) contains anomalous silver, gold and copper associated with metamorphosed calc-silicate alteration adjacent to a gabbroic intrusion. Abundant white mica, pervasive silicification and rare aluminosilicate minerals (andalusite?) indicate that hydrothermal alteration affected rocks in this area. Further prospecting in this rock unit is recommended.

Several gold showings occur in a variety of geological settings in the map area. Quartz vein hosted lode gold is typical of the McChesney ("B", *see* Figure 5.2) and Brookbank ("C", *see* Figure 5.2) showings. Sulphide-bearing, laminated and massive quartz veins are hosted in the Cairo stock syenite and are situated in northeast-striking shear zones or along north- and northwest-striking fractures and faults. Abundant hematite and rare purple fluorite suggest that oxidizing, alkalic fluids were associated with the mineralization.

Shear zone hosted gold mineralization is associated with the Galer Lake and Kinkaid faults, the Larder Lake–Cadillac deformation zone and associated subparallel shear zones. Disseminated pyrite is most closely associated with the gold mineralization but the type of associated hydrothermal alteration is dependent upon the host rock. For example, white mica, carbonate and porphyroblastic magnetite is common where shear zones cut Timiskaming metasedimentary or mafic alkalic metavolcanic rocks ("D", "L", *see* Figure 5.2). White mica, hematite, magnetite and rare barite occurs is some of the alkalic metavolcanic or syenitic host rocks ("F", *see* Figure 5.2) and chlorite, carbonate and hematite occur in some of the mafic and intermediate metavolcanic host rocks ("G", "H", "I", "J", *see* Figure 5.2).

Porphyry-style copper-gold mineralization hosted in the Cairo stock syenite occurs along the boundary of Flavelle and Cairo townships ("E", *see* Figure 5.2). Stringer and disseminated chalcopyrite and pyrite contains anomalous gold and is accompanied by hematite alteration with rare barite and fluorite veins. Disseminated pyrite and chalcopyrite occurs on the north shore of Galer Lake in aplitic syenite and there is potential for gold mineralization in this area ("M", *see* Figure 5.2).

One of the more intriguing gold showings occurs in sericite and hematite altered siltstone of the Gowganda Formation in central Burt Township ("K", *see* Figure 5.2). A diamond-drill hole targeted to penetrate the Gowganda Formation to reach the Larder Lake–Cadillac deformation zone intersected a narrow pyritic zone (0.5 m wide) in the Gowganda Formation that returned 500 ppb Au when assayed. Powell and Hodgson (1992) reported similar results from the Gowganda Formation in Quebec and concluded that the gold was remobilized from an Archean basement source over the Larder Lake–Cadillac deformation zone. The showing in Burt Township supports this conclusion and indicates that further exploration under the Gowganda Formation is warranted.

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6. Project Unit 03-002. Synthesis and Timing of Archean Geology and Diamond-bearing Rocks in the Michipicoten Greenstone Belt: Menzies and Musquash Townships

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INTRODUCTION

This summer's mapping project followed up on last year's mapping of Menzies Township. Part of the summer was spent completing and revising the mapping of Menzies Township with the goal of publishing a map at 1:20 000 scale in December of 2004. The remainder of the summer was used to map the southwest portion of Musquash Township and to start reconnaissance work in Lalibert and Leclaire townships. These 3 townships were mapped at 1:15 840 scale by R.P. Sage between 1981 and 1988, as part of a detailed study of the Michipicoten greenstone belt (Sage 1994, 1993a, 1993b). Remapping of Musquash, Lalibert and Leclaire townships is expected to be completed within the next 2 years, and will be combined with Menzies Township to produce a compilation map at 1:50 000 scale.

REGIONAL GEOLOGY

The map area is located approximately 12 km north of the town of Wawa. It is part of the Michipicoten greenstone belt, which is the largest greenstone belt of the Wawa Subprovince. In the Michipicoten greenstone belt, 3 volcanic assemblages were defined by Williams et al. (1991). They are the Hawk, Wawa and Catfish assemblages and they correspond to volcanic cycles 1, 2 and 3 described by Sage (1994 and references cited therein). The ages of the 3 assemblages are circa 2900 Ma, 2750 Ma and 2700 Ma, respectively (Turek, Smith and Van Schmus 1982, 1984; Turek, Sage and Van Schmus 1992).

A more detailed description of the regional geology is available in Vaillancourt, Wilson and Dessureau (2003), which also includes references to previous work.

MAP AREA

Mafic, intermediate and felsic Archean metavolcanic rocks along with mafic to intermediate intrusive rocks and minor iron formation form most of the map area (Figure 6.1). The southwest portion of Menzies Township consists of a sequence of intermediate to felsic intrusive rocks that have a range of compositions including mostly granite, granodiorite, tonalite and quartz-gabbro. A variety of breccias typically associated with lamprophyric dikes are found within the metavolcanic units in the central portion of the map area. Both the breccias and dikes locally host diamond occurrences. The Archean formations are cut by a variety of Paleoproterozoic to Mesoproterozoic diabase dike swarms.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.6-1 to 6-9.

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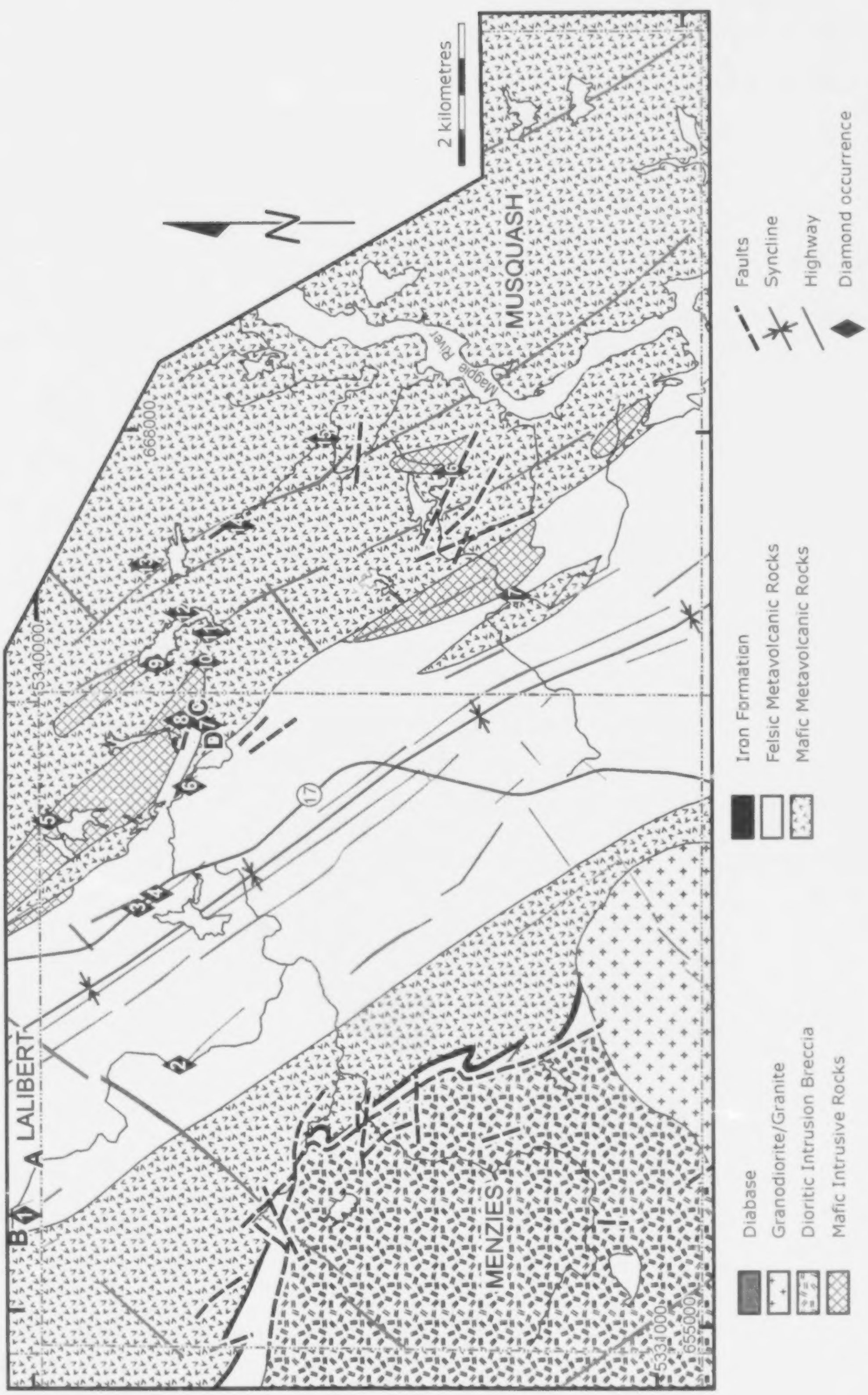
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N
MUSQUASH
Magpie River
LALIBERT
MENZIES
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5331000
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7
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9
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11
12
13
14
15
16
Diabase
Granodiorite/Granite
Dioritic Intrusion Breccia
Mafic Intrusive Rocks
Iron Formation
Felsic Metavolcanic Rocks
Mafic Metavolcanic Rocks
Faults
Syncline
Highway
Diamond occurrence

Figure 6.1. General geology of Menzies and Musquash townships. Diamond occurrences are 1 - Enigma (Arctic Star Diamond Corp. and Oasis Diamond Exploration Inc.); 2 - Dumont Sample 4073 (Dumont Nickel Inc.); 3 - MEN-107, 4 - MEN-106 (Spider Resources Inc., KWG Resources Inc., Diagem International Resources Corp.); 5 - Veuve Cliquot, 6 - Moet, 7 - Mumm, 8 - Genesis, 9 - Dom Perignon, 10 - Pommery, 11 - West Perch, 12 - East Perch, 13 - Salon, 14 - Crystal (Pele Mountain Resources Inc.); 15 - Area E, 16 - Area D, 17 - Area A (Band Ore Resources Ltd.). Letters are locations for samples submitted for geochronological analyses as discussed in the text.

Previous bedrock mapping suggests that the volcanic assemblages underlying Musquash Township and the northeast part of Menzies Township belong to the Catfish assemblage, which overlies rocks from the Wawa assemblage in central Menzies Township. Geochronological studies by Ayer et al. (2003), and new results (discussed further below) confirm this interpretation for the Catfish assemblage. Complementary geochronological studies to verify the presence of rocks belonging to the Wawa assemblage are underway and results are expected in spring 2005.

Mafic and Ultramafic Metavolcanic Rocks

The mafic to intermediate flows that are present in the northeast portion of Menzies and a large portion of Musquash townships are largely pillowed, with some local massive portions. Geochemical results from samples in Menzies Township reveal that they are tholeiitic in affinity. The presence of amphibole and plagioclase phenocrysts in mafic flows in southern Musquash Township suggests a more calc-alkalic affinity for this portion, but new geochemical analysis is required to ascertain this possibility.

The mafic to intermediate flows have locally been intensely recrystallized. These portions show large crystals (up to 3 cm) of hornblende, typically concentrated in or near the pillow selvages. The rocks also contain a significant amount of carbonates and are believed to be the result of metamorphism of a previously altered flow.

Felsic to Intermediate Metavolcanic Rocks

A very large proportion of the felsic to intermediate metavolcanic rocks in the map area is fragmental in nature, as only small, very localized massive rhyolitic flows have been recognized. The felsic assemblage is dominantly composed of tuff breccias, lapilli tuffs and tuffs. Previous geochemical studies indicate that they are calc-alkalic in composition. Biotite is the most common mafic mineral in the felsic metavolcanic rocks in general, but chlorite and hornblende are also locally present.

The most abundant and continuous unit is a tuff breccia to lapilli tuff. The composition of the fragments and that of the matrix are highly variable from felsic to intermediate, and a combination of felsic matrix with intermediate fragments and vice versa is not uncommon. Pumice fragments are locally abundant. Some breccias also contain large mafic fragments. The breccias commonly have plagioclase and/or quartz crystals in fragments and/or in the matrix.

Other units in the felsic to intermediate metavolcanic package of rocks include felsic tuff with quartz and plagioclase crystals, intermediate tuff, and finely laminated ash flows. The felsic and intermediate tuffs are strongly recrystallized so primary textures are commonly obliterated, leaving a massive and homogeneous appearance to the rocks. However, they are all interpreted to be tuffs rather than massive flows or sills because of the presence of local graded bedding and intercalated lapilli-tuff finely laminated ash flows horizons.

Massive rhyolite flow was recognized only on a few small outcrops. This unit is very siliceous and shows fine flow banding. Contact relationship with surrounding tuffs was not exposed and therefore remains uncertain.

Iron Formation

A northwest-oriented, very narrow banded iron formation is present in the centre part of Menzies Township. It is largely composed of variable proportions of chert-rich and magnetite-rich centimetre-scale beds, with local sulphide-rich horizons. The iron formation is typically underlain to the southwest by very siliceous, highly deformed (mylonite) rocks of uncertain parentage. Although the iron formation forms a wide positive magnetic anomaly on airborne geophysical survey maps (Ontario Geological Survey 1999, 2003), it is typically only a few metres thick throughout the map area. The shallow to sub-horizontal dip observed in the iron formation is likely responsible for the broad high magnetic anomaly on the magnetic map. Its extension toward the northwest into areas that were mapped by R.P. Sage (Sage 1993a) indicates that this iron formation lies above felsic metavolcanic rocks of the Wawa assemblage (cycle 2). Rocks of this assemblage have only been recognized in the northwest part of Menzies Township. The iron formation and underlying chert are in sheared contact with the felsic to intermediate intrusive rocks that form the southwest corner of Menzies Township.

The iron formation located in the northeast portion of Musquash Township also appears to be a narrow unit within felsic metavolcanic rocks. Only reconnaissance mapping was done in this portion of Musquash Township and more detailed mapping will be conducted next summer to better understand its contact relationships with the surrounding rocks. This iron formation may be a structurally repeated part of the Wawa assemblage.

Felsic to Intermediate Intrusive Rocks

A felsic to intermediate complex underlies the southwest portion of Menzies Township. This complex includes a variety of lithologies, including gneisses of uncertain protolith. The complex is made of granite, granodiorite, tonalite, diorite, quartz-gabbro and gneiss that may contain a large amount of garnet. With the exception of the quartz-gabbro, all units in the complex contain both biotite and muscovite, and preliminary geochemical studies indicate that they are peraluminous. The contact relationships between the different units is complex but the mafic units are typically found as inclusions of various sizes, and the felsic units are typically dikes that cut all other units. Garnet-bearing gneisses were found in a number of areas within the complex. Because of their total recrystallization, the protolith is difficult to identify. Detail mapping deeper into the complex in the adjacent townships will be necessary to better understand its origin and nature. The portion that is present in Menzies Township appears to represent a mixed brecciated border of the complex.

A more massive and homogeneous granodiorite body occurs in the central portion of the southern boundary of Menzies Township. This unit is coarse grained and contains a large amount of quartz. No contacts were observed but the granodiorite is in close proximity to the adjacent mafic metavolcanic rocks, into which they may be intruded.

Mafic Intrusive Rocks

Synvolcanic gabbro dikes that are geochemically similar to the mafic metavolcanic rocks are found throughout the map area. These are commonly associated with the mafic metavolcanic rocks, but also cut the felsic metavolcanic rocks, particularly near the contact with the mafic metavolcanic rocks. A number of mafic dikes with similar geochemistry are also found cutting the felsic to intermediate intrusive complex located in the southwest corner of Menzies Township. These could be interpreted to represent feeders to the mafic metavolcanic rocks of the Catfish assemblage, but may also be units unrelated to this assemblage. Further mapping and a better understanding of the complex will be required to assess the various possibilities.

Gabbro is relatively abundant in Musquash Township. They appear to be generally less deformed than the mafic metavolcanic rocks that they are closely associated with. These gabbros are common hosts to the breccias and ultramafic and mafic dikes in which diamonds were found (discussed further below).

Their absolute timing of emplacement is uncertain and geochemical and petrological studies will be necessary to determine if they are related to the mafic metavolcanic rocks or if they are part of a younger magmatic event.

Northwest-striking diabase dikes in the map area are interpreted to be part of the Matachewan and Hearst swarms. These dikes are undeformed and many contain plagioclase glomerocrysts, which are typical of these swarms. They have a sub-ophitic texture, mainly composed of blades of plagioclase and sub-idiomorphic clinopyroxene. Amphibole forms coronas of various widths on the pyroxene, locally replacing them entirely. Magnetite is relatively abundant and biotite is also present but scarce.

A broad northeast-striking olivine-diabase dike, interpreted to belong to the Keweenawan swarm intrudes the rocks in the northwest corner of Menzies Township. In the map area, this dike has an ophitic texture and is composed mostly of idiomorphic plagioclase and olivine, and oikocrysts of clinopyroxene. Biotite and magnetite are also present.

A third type of northeast-striking dikes is present in southeast corner of Menzies Township. Varitextured phases have been observed in these dikes along with local small carbonate veins, features that are generally atypical for Proterozoic diabase dikes (Photo 6.1). Petrographic examination of these dikes revealed an ophitic to sub-ophitic texture formed by plagioclase and clinopyroxene. The pyroxenes are partially altered to amphiboles and minor biotite, and variable amounts of carbonates are also present in these rocks. Although these dikes share some similarities with the dikes from the Matachewan and Heart swarms, they are generally more altered and preliminary geochemical results indicate that they are significantly different. Their possible parentage is currently under investigation.

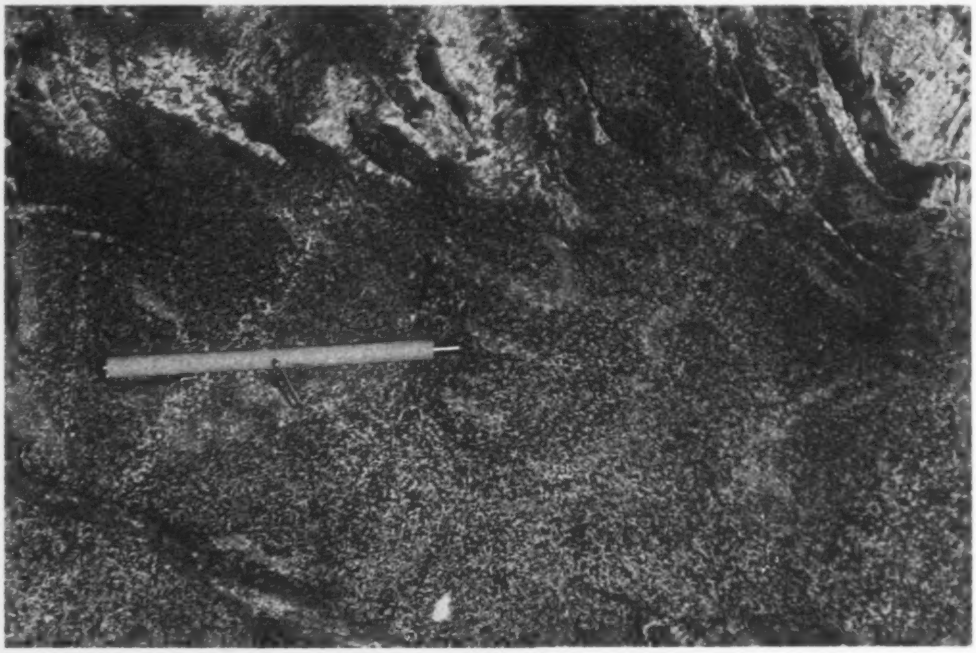

Photo 6.1. Varitextured gabbro dike with carbonate veins.

Diamond-bearing Breccias and Lamprophyric Dikes

Diamond occurrences have been found in various fragment-supported breccias and associated lamprophyric rocks located in Menzies, Musquash, Lalibert and Leclaire townships. These rocks have been observed to intrude into the mafic and felsic metavolcanic rocks of the Catfish assemblage and into a gabbro of uncertain age. As geochronology indicates (see below), these breccias and lamprophyre dikes are significantly younger than the volcanic assemblage they are intruding, which indicates that they thus represent a separate late intrusive event.

There seems to be a compositional continuum between the breccias and the dark lamprophyric rocks with intermediate units containing various amounts of fragments and a lamprophyric matrix. The matrix is generally composed of biotite, actinolite or talc, any combination of two, or all three minerals. Carbonates are generally present in various amounts and some breccias also contain quartz in their matrix. The size of the fragments varies from millimetre to metre scale. A large portion of these fragments are felsic and mafic metavolcanic rocks and gabbros. The more exotic populations include radial-textured actinolite-talc-carbonate fragments, talc fragments with chromium-chlorite blebs and fine-grain biotite porphyritic dark fragments of uncertain composition. These exotic fragments will be the focus of targeted geochemistry and petrographic studies as they represent excellent candidates as host to the diamonds within the breccias.

Timing of the Metavolcanic and the Diamondiferous Intrusive Units

Uranium-lead (U/Pb) zircon geochronological work has been ongoing to help better understand the nature and timing of the diamondiferous units and their host rocks and to test the hypothesis that the diamondiferous breccia units were volcaniclastic units intercalated with the Catfish assemblage. Previously reported results (Ayer et al. 2003) included an age of 2701.4±2.1 Ma from a felsic metavolcanic unit hosting diamondiferous units (*see* Figure 6.1, Sample A) and maximum ages of 2685.0±1.0 Ma and 2684.9±1.4 Ma for diamondiferous lamprophyre dikes cutting the supracrustal units in Lalibert Townships (*see* Figure 6.1, Sample B).

In order to further test the age of the metavolcanic units hosting the diamondiferous rocks, a sample of felsic lapilli tuff adjacent to the Moet showing (Festival Diamond Property, Pele Mountain Resources Inc.) was sampled in Menzies Township (*see* Figure 6.1, sample C). A limited number of zircons were recovered from this sample, and many of these contained altered zones and cracks. The best of these were fragments of simple, four-sided needles. Three individual fragments were analyzed for U and Pb and these gave consistent results (Figure 6.2A), two of which are concordant (sk17p86-87) and give a weighted mean $^{207}Pb/^{206}Pb$ age of 2698.7±1.1 Ma (95% probability of fit). The third datum (sk17p85) is 0.5% discordant and a regression line calculation through all three points gives an upper intercept age of 2698.5+2.5/–1.3 Ma (85% probability of fit). By comparison, if all 3 data are included in a weighted mean $^{207}Pb/^{206}Pb$ age calculation, the age is 2698.4±1.1 Ma (35% probability of fit). The most robust age interpretation is the mean $^{207}Pb/^{206}Pb$ age of the 2 concordant points of 2698.7±1.1 Ma.

Lamprophyre dikes cut the diamondiferous breccias (Photo 6.2) and thus are at least slightly younger than the breccias. Therefore, in order to test the age of brecciation, a sample of diamondiferous breccia from the Moet showing was collected for geochronology (*see* Figure 6.1, Sample D). A moderate yield of mostly altered and cracked zircons was recovered from this rock sample. A subpopulation of euhedral, translucent zircons is present and approximately two dozen grains were selected for air abrasion. Five of the best of these were analyzed (sk17p70-74) and concordant data was obtained for each of them (Figure 6.2B). The 3 oldest ages are 2687±2 Ma (sk17p74), 2683±2 Ma (sk17p71) and 2681±2 Ma (sk17p70). The 2 youngest zircons from this sample give data that precisely overlap each other at 2679.2±2.1 Ma (sk17p72-73). This is the youngest zircon age obtained from the breccia and it represents either the time of crystallization or emplacement of the body, providing the zircons are magmatic, or a maximum time of emplacement if the zircons are xenocrystic. There is no supporting information in this study that can guarantee these younger zircons crystallized in the breccia matrix. However, it is quite possible that this age is at least very close to the time of emplacement of the breccia as titanite, with an age of 2674±8 Ma, from a lamprophyre dike in Musquash Township (Stott et al. 2002) is well within error of the age reported here.

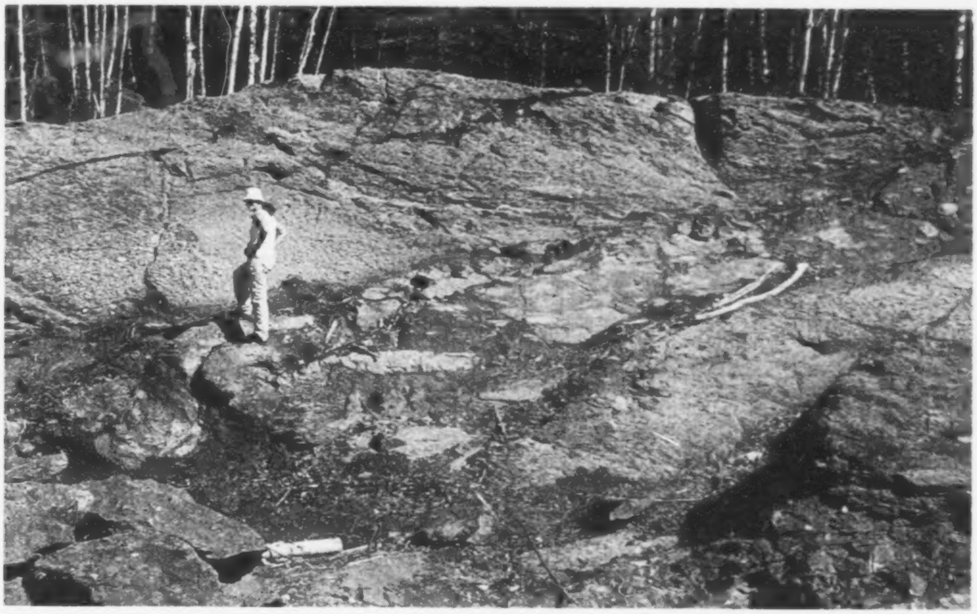

Photo 6.2. Lamprophyric dike cutting diamondiferous breccia at the Moet occurrence, Festival Property (Pele Mountain Resources Inc.).

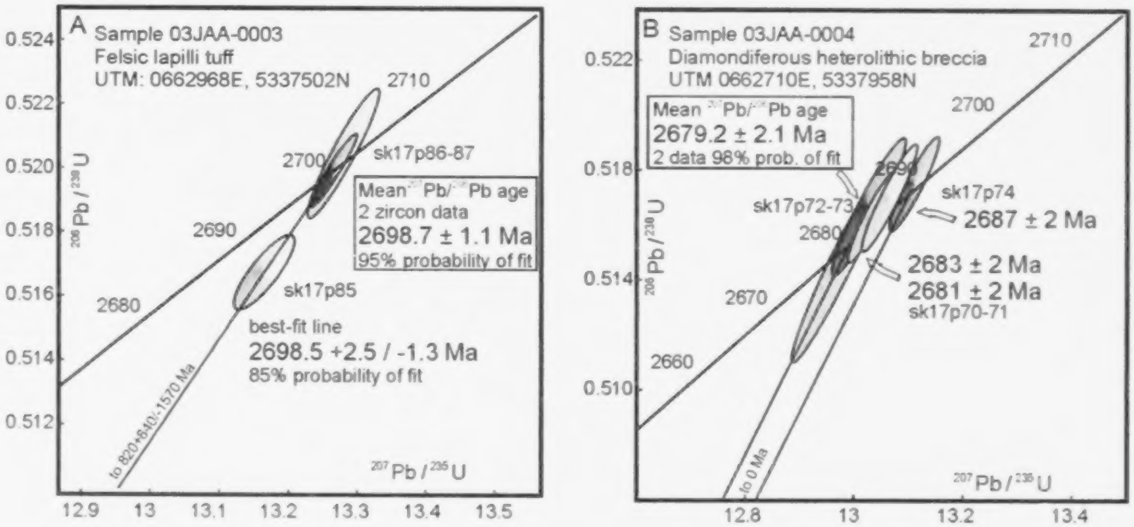

Figure 6.2. Concordia diagrams with U/Pb analyses for zircon. Ellipses indicate the 2σ uncertainty.

The above data indicate that felsic metavolcanic units hosting the diamondiferous rocks are part of the Catfish assemblage and suggests that the unit in eastern Menzies Township may be slightly younger and from a higher stratigraphic part of the assemblage. The maximum age for the diamondiferous breccias and the associated dikes is well established at less than 2680 Ma. Collectively, these absolute age constraints indicate that the breccias are not volcaniclastic, but are related to a volatile-rich diatreme brecciation event in which mantle-derived diamonds were transported into the upper crust. Coeval but slightly younger diamondiferous lamprophyre dikes also host diamonds in generally lower abundances than the breccias, which suggests that the more rapid transportation to surface within the diatremes may have been an important criteria for diamond concentrations.

Structure

Observations made in Musquash Township this summer are consistent with previous interpretations (Vaillancourt, Wilson and Dessureau 2003) that a large overturned fold with a northwest-trending axial plane (*see* Figure 6.1) is responsible for stratigraphic repetition of the rocks from the Catfish assemblage and possibly the underlying Wawa assemblage. This interpretation is based on overturned and southwest-younging direction in pillowed flows in eastern Menzies and all of Musquash Township, and northeast-younging direction in northwest Menzies Township. An axial planar penetrative schistosity associated with this folding event is well developed throughout the map area. Localized discontinuous shear zones oriented northwest to east are also common. These observations are similar to those made by Arias and Helmstaedt (1990) immediately east of the map area for the deformation episode that they have named D_2.

In Menzies Township, a second episode of deformation, discussed in Vaillancourt, Wilson and Dessureau (2003), is represented by low-amplitude folds with a steeply dipping north to northeast axial plane. This episode is not as well developed in Musquash Township. Weak penetrative foliation may be associated with these folds, but it is generally absent. This episode is equivalent to the D_3 event described by Arias and Helmstaedt (1990).

Metamorphism

Generally, the mineral assemblages in the mafic and felsic metavolcanic rocks of the map area are indicative of greenschist-facies regional metamorphism. Grain size reduction makes mineral identification extremely difficult in the field. These textures may be the result of multiple, superimposed episodes of metamorphic recrystallization. This will be investigated further through ongoing petrographic work complemented by mineral chemistry.

RECOMMENDATIONS FOR EXPLORATION

At this time, very little is known about the nature and origin of the diamond-bearing breccias and associated rocks. As diamonds have been recovered from a variety of breccias and lamprophyre dikes, it becomes very important to determine where the diamonds are located within these units. Because different breccias cut one another at the location of the diamond occurrences, a large proportion of the samples that were processed for diamond recovery in the past have potentially included more than one unit. It is imperative that small samples representing only one specific unit be processed for diamond recovery in order to determine which unit or units actually contain diamonds. Once this is assessed, efforts should be made to determine which component of the breccias (matrix versus a specific type of fragment) host the diamonds. Carefully selected samples were collected for caustic dissolution in hope to address this problem.

The results of the geochronological studies support the possibility that the diamond-bearing rocks may be genetically associated with the alkalic plutonism in the area. Lamprophyric dikes are commonly associated with late mantle-derived suites, which include sanukitoids and alkalic plutons in the Superior Province (Stern and Hanson 1992, and references cited therein; Berger 2002) and so further investigation of these units may be of interest for new discoveries. However, until precise geochronological work and mapping are completed on the Dickenson Lake alkalic pluton and surrounding areas, these ideas remain theoretical.

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7. Project Unit 00-011. Geology and Mineral Potential of Carman and Langmuir Townships, Shaw Dome Area

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INTRODUCTION

The Precambrian Geoscience Section of the Ontario Geological Survey (OGS) conducted bedrock mapping at a scale of 1:20 000 in Carman and Langmuir townships as part of an ongoing project to update geological mapping in the Timmins mining camp. The current bedrock mapping project has completed the mapping of the entire Shaw Dome area (Figure 7.1). This project follows the bedrock mapping of Deloro Township in 2002 (Hall, MacDonald and Dinel 2003) and Shaw, Adams and Eldorado townships in 2003 (Hall, Houlé and Tremblay 2004; Houlé, Hall and Tremblay 2004).

As established last year (Hall and Houlé 2003), the goals of this multi-year project are four-fold:

1. to clarify some lithologic uncertainties and to refine lithologic and assemblage boundaries;
2. to better understand the stratigraphic and structural nature of the Shaw Dome;
3. to evaluate the mineral potential of the area; and
4. to study the ultramafic metavolcanic and intrusive rocks.

Goals 3 and 4 are briefly discussed in a subsequent section of this paper, but will be addressed in more details in a collaborative OGS–Discover Abitibi Open File Report to be released in 2005. Geophysical and diamond-drill hole data are being used to aid in the extrapolation of geological contacts across the many large areas obscured by thick overburden.

REGIONAL SETTING

Drawing analogies with plate tectonic models, Jackson and Fyon (1991) subdivided the Abitibi greenstone belt into over 50 different assemblages, which they suggested represented accreted allochthonous *terranes*. However, recent work has defined a new stratigraphic framework of 9 distinctive assemblages within the Abitibi greenstone belt in Ontario, interpreted to have developed autochthonously (Ayer et al. 1999a, 1999b). In these new assemblages, 7 are dominantly volcanic and 2 are dominantly sedimentary. The Abitibi greenstone belt consists of a stratigraphically continuous succession of Archean metavolcanic and metasedimentary rocks that developed in an ensimatic basin (Ayer et al. 2002).

With the exception of Paleo- and Mesoproterozoic dikes, all the bedrock in the Shaw Dome area is Archean. Recent bedrock mapping and geochronological work done by the Ontario Geological Survey, since 2002 in this area, suggests that the supracrustal rocks could be subdivided into 4 distinct supracrustal packages: *Supracrustal Package A*, *Supracrustal Package B*, *Supracrustal Package C*, and *Supracrustal Package D* (*see* Figure 7.1).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.7-1 to 7-16.

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Supracrustal Package A is located in the central portion of the Shaw Dome structure and can be found within all townships in the area. However, this package crops out mainly in Shaw and Deloro townships, in the northern part of Eldorado Township, and in southwest Carman Township. Supracrustal Package A is composed dominantly of a coherent facies of calc-alkalic intermediate to mafic metavolcanic rocks with lesser intermediate volcaniclastic rocks. Flows are pillowed to massive, commonly amygdaloidal and plagioclase-phyric. This package is a part of the Deloro assemblage defined by Ayer et al. (1999b) and also equivalent to the Deloro assemblage defined by Jackson and Fyon (1991).

Supracrustal Package B is located in the south part of the Shaw Dome structure including the southwestern part of Carman Township, the western part of Langmuir Township, the northern part of Eldorado and Adams townships, and the south part of Deloro Township. Package B consists of intermediate to felsic fragmental metavolcanic rocks (lesser coherent facies), iron formation, and ultramafic flows and intrusions. This package could be interpreted as part of the Deloro or Tisdale assemblages defined by Ayer et al. (1999b) based on the previous geochronological data available for this area. This package is equivalent to the Eldorado assemblage described by Jackson and Fyon (1991). However, recent mapping done in this area suggests that package B is more likely related to the Deloro assemblage rather than the Tisdale assemblage based on the presence of calc-alkalic metavolcanic rocks, abundant iron formation, and lack of geochemical discontinuity with package A.

Supracrustal Package C is located outside the Shaw Dome structure and is present within all townships in the area. However, this package crops out mainly in the northeast part of Shaw Township, the east part of Carman and Langmuir townships, the south part of Eldorado Township, the northwest part of Adams Township and the southwest part of Deloro Township. This supracrustal package consists of a coherent facies (pillowed to massive) of tholeiitic mafic metavolcanic rocks intercalated with a coherent facies (massive to organized flows) of komatiitic basalt and komatiite metavolcanic rocks. This package is interpreted as part of the Tisdale assemblage defined by Ayer et al. (1999b) and corresponds to the Bowman assemblage described by Jackson and Fyon (1991).

Supracrustal Package D is located exclusively in the northern part of Deloro Township within a highly strained zone, approximately 100 m wide and interpreted as the Porcupine–Destor deformation zone (L.A.F. Hall, OGS, personal communication, 2003). This package is essentially composed of felsic fragmental metavolcanic rocks, with abundant lapilli size fragments, including some "fuchsitic" or green mica fragments and rare quartz eyes. *Supracrustal Package D* is interpreted as Krist formation felsic metavolcanic rocks based on new geochronological data obtained in Ogden Township along strike (Ayer et al. 2003). This package is a part of the Porcupine sedimentary assemblage defined by Ayer et al. (1999b) and does not have any equivalent within the old nomenclature of Jackson and Fyon (1991).

ARCHEAN ROCKS

Only 3 supracrustal packages have been identified in Carman and Langmuir townships: Supracrustal Packages A, B and C (Figure 7.2). However, this may be subject to revision when the lithogeochemical, geochronological and petrographic results have been assessed.

Supracrustal Package A

Intermediate to mafic metavolcanic rocks with lesser intermediate to felsic metavolcanic rocks and siliceous iron formation horizons dominate Supracrustal Package A. This supracrustal package has a limited extend in the map area and covers only the northwest corner of Langmuir and the southwest corner of Carman townships. All of these rocks display a weak to moderate tectonic fabric and are metamorphosed to lower greenschist facies.

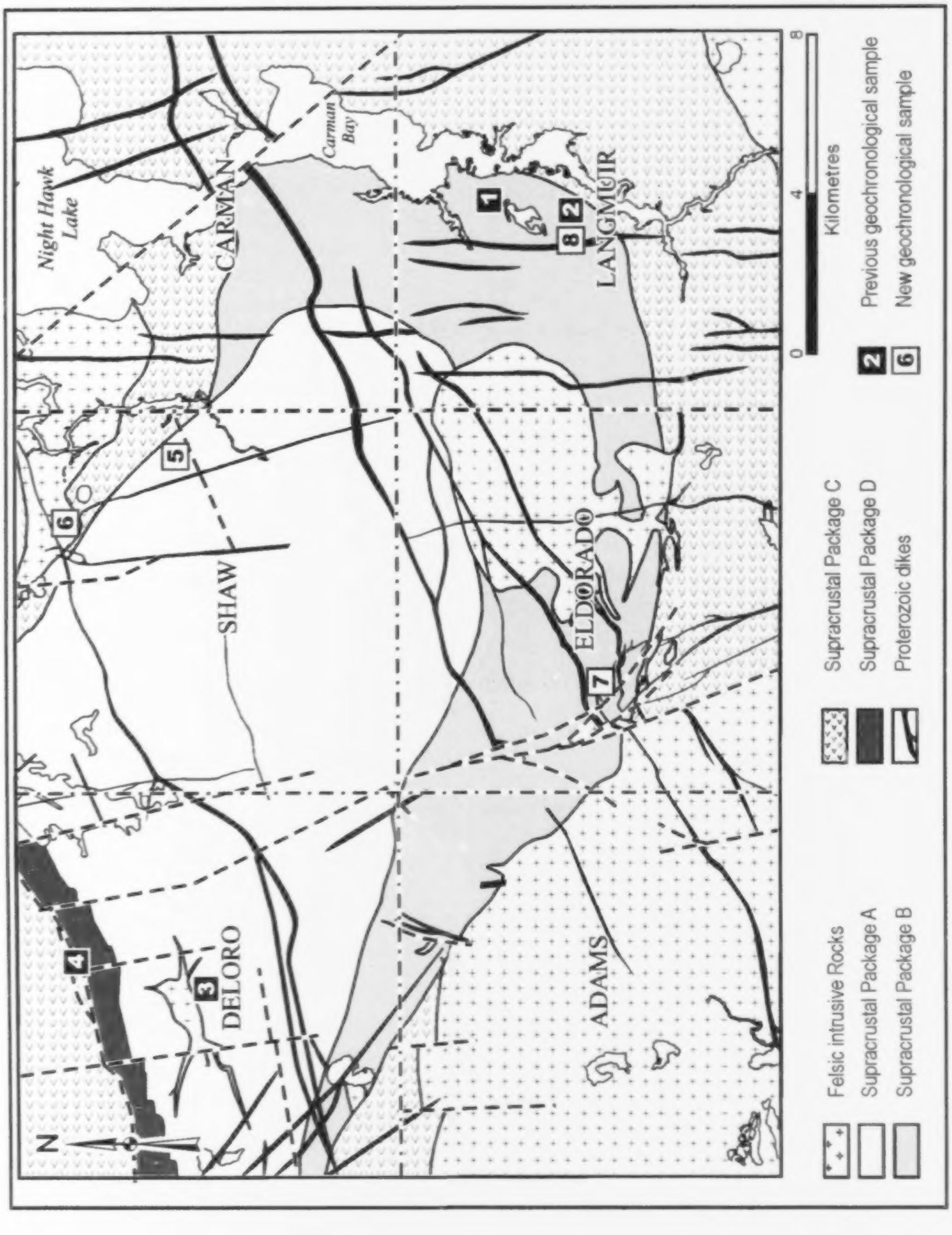
N
Night Hawk Lake
CARMAN
Carman Bay
SHAW
DELORO
ADAMS
ELDORADO
LANGMUIR
1
2
3
4
5
6
7
8
0
4
8
Kilometres
Felsic intrusive Rocks
Supracrustal Package A
Supracrustal Package B
Supracrustal Package C
Supracrustal Package D
Proterozoic dikes
Previous geochronological sample
New geochronological sample

Figure 7.1. General geology of the Shaw Dome area with Supracrustal Package and geochronological sample locations.

INTERMEDIATE TO MAFIC METAVOLCANIC ROCKS

Intermediate to mafic metavolcanic rocks of Supracrustal Package A typically display a pale buff-green weathering surface and a medium to dark grey-green fresh surface. They display well-preserved primary structures including massive flow, volcaniclastic deposits, and lesser pillowed flows.

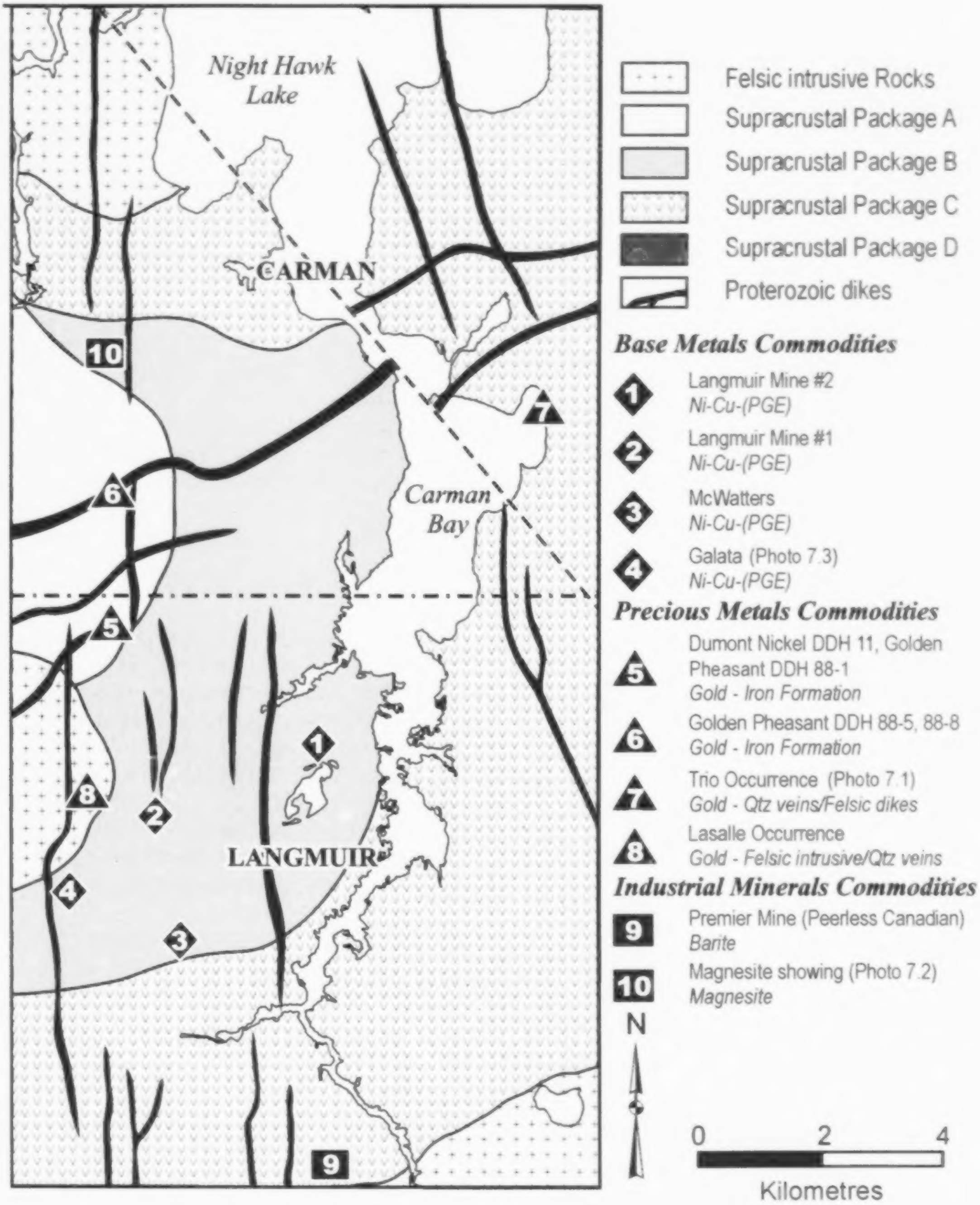
Night Hawk Lake
CARMAN
Carman Bay
LANGMUIR
10
6
5
8
2
1
4
3
7
9
Felsic intrusive Rocks
Supracrustal Package A
Supracrustal Package B
Supracrustal Package C
Supracrustal Package D
Proterozoic dikes
Base Metals Commodities
1 Langmuir Mine #2 Ni-Cu-(PGE)
2 Langmuir Mine #1 Ni-Cu-(PGE)
3 McWatters Ni-Cu-(PGE)
4 Galata (Photo 7.3) Ni-Cu-(PGE)
Precious Metals Commodities
5 Dumont Nickel DDH 11, Golden Pheasant DDH 88-1 Gold - Iron Formation
6 Golden Pheasant DDH 88-5, 88-8 Gold - Iron Formation
7 Trio Occurrence (Photo 7.1) Gold - Qtz veins/Felsic dikes
8 Lasalle Occurrence Gold - Felsic intrusive/Qtz veins
Industrial Minerals Commodities
9 Premier Mine (Peerless Canadian) Barite
10 Magnesite showing (Photo 7.2) Magnesite
N
0
2
4
Kilometres

Figure 7.2. General geology of Carman and Langmuir townships showing the different supracrustal packages and the main mineral occurrences and their commodities.

The intermediate to mafic volcaniclastic rocks display a range of characteristics. Fragments that are more siliceous (intermediate in composition) than the matrix have a pale weathered (chloritized matrix) surface and stand out in positive relief on the outcrop surface in comparison with the matrix. The fragments in these exposures range in size (lapilli to blocks), abundance (fragment to matrix supported) and composition (mainly intermediate to mafic fragments, but including some chert fragments locally, displaying a range of textural characteristics).

Supracrustal Package A is composed of intermediate to mafic metavolcanic flows that are commonly porphyritic with feldspar phenocrysts. Amygdules are present in most intermediate metavolcanic rocks in varying abundances and sizes. Carbonate (typically calcite), quartz, and quartz-rimmed carbonate fillings are most common, while chlorite + quartz ± carbonate fillings are locally present. A vesicular appearance on the weathered outcrop surface occurs where the carbonate fillings have been weathered out and dissolved.

FELSIC TO INTERMEDIATE METAVOLCANIC ROCKS

Felsic to intermediate metavolcanic rocks of Supracrustal Package A are stratigraphically interleaved with the more mafic metavolcanic rocks. They are pale chalky buff on weathered surfaces and pale to medium green-grey or yellow-grey or dark grey on fresh surfaces. The presence of sericite, relatively low abundance of chlorite and their relative hardness also helps to characterize the composition of these rocks.

Felsic to intermediate metavolcanic rocks also display a variety of primary characteristics including volcaniclastic deposits (lapilli and block) with lesser massive flows. Both porphyritic and aphyric textures were noted. Phenocryst compositions are mainly feldspar, and rarely feldspar and quartz and their abundance ranges up to 15%. Amygdules are locally very abundant in the more intermediate rocks of this unit.

SILICEOUS IRON FORMATION

Siliceous banded iron formation is exposed near the stratigraphic top of Supracrustal Package A. Iron formations are generally oxide-bearing (magnetite ± hematite). The oxide-bearing iron formation commonly consists of thin layers of dark grey to black, very fine-grained magnetite alternating with thicker cherty layers. The iron formation contains disseminated pyrite that locally appears to be associated with the presence of quartz and quartz-carbonate veins. This has been interpreted to indicate that the sulphide minerals formed as a result of sulphidization and replacement of primary magnetite. Quartz veins, locally more than 2 m wide, are common throughout the iron formation.

A distinctive horizon of dismembered chert hosted in a matrix of intermediate to mafic metavolcanic rock is also present in the south part of Carman Township. Further investigation will determine if this unit could be used as marker horizon throughout the entire Shaw Dome (also observed in Deloro and Shaw townships). The iron formation horizons, though laterally varied and locally discontinuous, should provide stratigraphic markers to aid in the construction of geological maps and in the interpretation of both the stratigraphy and the structural complexities of the Shaw Dome.

Supracrustal Package B

Supracrustal Package B is only found along the west flank of the Shaw Dome in Carman and Langmuir townships. It consists of intermediate to felsic metavolcanic rocks, ultramafic metavolcanic and intrusive rocks and felsic metavolcanic rocks with lesser iron formation. All of these rocks display a moderate to strong tectonic fabric and are metamorphosed to lower greenschist facies. With the exception of the ultramafic rocks, these rocks display significantly more strain than the rocks of Supracrustal Package A.

INTERMEDIATE TO FELSIC METAVOLCANIC ROCKS

Intermediate to felsic metavolcanic rocks of Supracrustal Package B are typically medium buff-beige on the weathered surfaces and medium to dark grey on the fresh surfaces. Flattened to highly flattened fragmental and massive metavolcanic rocks are present. Fragment size varies from ash to blocks. Quartz, carbonate and quartz-carbonate amygdules are present in the metavolcanic flows. Unusual magnetite-bearing tuff breccia to pyroclastic breccia that was found last year was not observed in the map area.

FELSIC METAVOLCANIC ROCKS

Few exposures of felsic metavolcanic rocks are dominated by fragmental volcanic facies and occur in central and east-central Langmuir Township within Supracrustal Package B. These siliceous rocks are medium to pale buff-beige and chalky with pale yellow-green patches on the weathered surfaces. Fresh surfaces are white to medium grey. Lapilli-tuff, but some volcanic *in-situ* breccia, and massive flows are also present. These rocks are penetratively foliated throughout the area.

ULTRAMAFIC METAVOLCANIC ROCKS AND INTRUSIONS

The ultramafic rocks of Supracrustal Package B consist of intimately associated flows and high-level intrusive components. Determination of the intrusive versus extrusive origin of these rocks and the implications of these emplacement mechanisms is one of the goals of the Ni-Cu metallogenic theme of the collaborative subproject being conducted between OGS and the Discover Abitibi Initiative. Distinguishing between an intrusive or extrusive origin is difficult because of the scarcity of good surface exposures. Nonetheless, the ultramafic rocks within this package have been subdivided into 2groups. The first group, located lower in the stratigraphy, is interpreted to be more likely intrusive, whereas the second group, located higher in the stratigraphy, is interpreted to be more likely extrusive.

The first group of ultramafic rocks has pale orange-brown or bone-white weathered surfaces and dark green or pale green fresh surfaces. Serpentinization is pervasive, but magmatic textures are generally well preserved. Primary mineralogy can be estimated, as the serpentine pseudomorphs primary igneous minerals (olivine, pyroxene). Most ultramafic exposures consist of dunite to peridotite, but some pyroxenites are locally present in association with the other more ultramafic components of this group.

The second group is characterized by pale orange-brown or bone-white weathered surfaces and dark green or pale green fresh surfaces, which is similar to the ultramafic rocks observed within the first group. However, well-preserved primary structures such as layered flows are present and exhibit massive cumulate or non-cumulate textures, spinifex textures, and lesser polyhedral jointing. Serpentine veins crosscut the flow units. Ultramafic rocks exposed in southwest Carman Township are generally less magnesium rich and are characterized by the presence of pyroxene spinifex texture and pillowed komatiitic basalts instead of true komatiites. Those rocks are also characterized by a strong carbonate alteration with abundant calcite, magnesite and iron carbonate minerals. Locally, this alteration completely obscures the primary features.

SILICEOUS IRON FORMATION

Iron formation horizons occur at different stratigraphic levels in Supracrustal Package B. Iron formations are poorly to well layered and essentially composed of cherty or sugary quartz bands interlayered with thin magnetite bands or orange limonite bands. Furthermore, some iron formations described by Pyke (1970) consist of alternation of cherty bands and dark grey, red, or black argillites. However, authors did not observe these facies. Many of the iron formations contain sulphide mineral bearing zones where pyrite is typically more abundant than pyrrhotite. Many iron formation units may contain massive or semi-massive sulphide horizons within the siliceous iron formations. However, they were observed only in some old trenches or diamond-drill cores in this area. These zones of sulphide mineralization explain quite a few magnetic geophysical anomalies and electromagnetic geophysical conductors in the Supracrustal Package B.

Supracrustal Package C

Exposure of Supracrustal Package C is much more common in the map area than it was in Shaw, Adams and Eldorado townships. This package is essentially located in the south and west parts of Langmuir Township and in the north and west parts of Carman Township. Exposure in this package is limited and bedrock exposures are scattered in various localities within the map area. Exposures are mainly concentrated along the shore of Night Hawk Lake, in Carman Bay as well as in the south part of Langmuir Township.

This sequence consists primarily of intercalated ultramafic metavolcanic rocks (komatiites and komatiitic basalts), mafic metavolcanic rocks (mafic to high-magnesium volcanic rocks) and rare graphitic argillite. Komatiites with lesser mafic metavolcanic rocks and rare graphitic argillite dominate the sequence in the southern part of the map area, whereas komatiitic basalt and high-magnesium metavolcanic rocks with lesser mafic metavolcanic rocks dominate in the northern part of the map area. All of these rocks display a weak tectonic fabric and are metamorphosed to lower greenschist facies. Thin felsic dikes intrude all units of this package.

MAFIC METAVOLCANIC ROCKS

Mafic metavolcanic rocks display a medium to pale green weathered surface with medium green fresh surfaces. Pillowed and massive flows are the two main volcanic facies in this package of rocks with pillowed flows being dominant. Pillows display a wide range of sizes, probably reflecting the composition range from mafic to ultramafic. Pillow shapes range from regular cuspate pillows (aspect ratios of 1:2), mushroom-shaped to amoeboid pillows (aspect ratio of 1:4), and lobate sheet or elongate pillows (aspect ratio of 1:10). The pillows exhibit thin, dark green pillow rims surrounded by vesicle-rich layers. Interpillow material is composed of breccia with mafic metavolcanic fragments or fine-grained hyaloclastite. Some cooling fractures were observed, but are less common than in the volcanic flows in Supracrustal Package A. Massive flows are devoid of primary structures, however, they locally display a fracture network similar to the polyhedral jointing typically found in komatiites and komatiitic basalts.

The mafic metavolcanic rocks that occur along the contact with the monzonite in the southern part of Langmuir Township and in the high-strain zone in east Langmuir Township are distinct in character. These rocks are mylonitized and amphibolitized with dark and pale green "streaks" due to the relative abundance of hornblende and epidote. These rocks are interpreted as pillowed and massive mafic metavolcanic rocks that are intimately associated with gabbro-amphibolite and highly strained felsic intrusive rocks.

ULTRAMAFIC METAVOLCANIC ROCKS

The komatiitic ultramafic metavolcanic rocks of Supracrustal Package C are pale orange-brown or bone-white weathering and dark green or pale green on the fresh surface. They display well-preserved primary structures including massive (cumulate and non-cumulate), spinifex textures, spinifex-veins and/or sills, polyhedral jointing and flow-top breccia.

Several, 2 to 15 m thick flows have been delineated within the ultramafic metavolcanic rocks and consist of massive and internally layered flows. The massive flows are olivine meso- to orthocumulates with polyhedral jointing locally developed at the top of the flow. Layered flows include a lower olivine orthocumulate zone and an upper spinifex zone. The upper contacts of the layered flows commonly display polyhedral jointing and sometime flow-top breccia. The relative thickness of these layered flows tends to decrease with the stratigraphy.

Serpentinization is the most predominant alteration in the ultramafic metavolcanic rocks. Serpentinization is pervasive and serpentine veins crosscut the flows, but most of the primary textures are well preserved. Furthermore, locally intense and pervasive carbonate alteration occurred in the southeast part of Langmuir Township and destroyed most primary textures. However, some well-preserved spinifex textures were observed in these highly altered ultramafic rocks at several localities.

GRAPHITIC ARGILLITE

Except for iron formation throughout Supracrustal Packages A and B in the Shaw Dome, the only other metasedimentary rocks present in the map area are some thin layers of sulphide-bearing graphitic argillite. It consists of very fine-grained dark material with some disseminated pyrite and lesser pyrrhotite. These units do not crop out anywhere in the map area. They have only been observed in diamond-drill core located near the Forks River in Langmuir Township.

Archean Mafic Intrusions[3]

Supracrustal rocks of all packages are intruded by mafic intrusions. These rocks are typically fine- to medium-grained gabbro consisting of plagioclase, amphibole and chlorite. Limited fabric development, a characteristic diamond-shaped joint pattern, and an absence of volcanic structures and textures distinguish these rocks from the fine-grained metavolcanic rocks they intrude.

Archean Felsic Intrusions

MONZONITIC AND TONALITIC INTRUSIONS

The extent of felsic and intermediate intrusive bodies is very limited in the map area. The largest of these is a tonalitic intrusion ("Eldorado pluton") that underlies approximately 15 km^2 of east-central Eldorado and west-central Langmuir townships. This intrusion is a medium- to fine-grained massive to weakly foliated equigranular tonalite. The primary mineralogy is composed of quartz, plagioclase, and 10 to 15% ferro-magnesian minerals (hornblende, biotite). Some disseminated magnetite was locally observed. This intrusion is also characterized by a slight to moderate level of epidotization and hematization.

The monzonitic intrusion extends from northeast Fallon Township into the south corner of Langmuir Township. Exposure of this intrusion is limited within the map area and most of the outcrops are hybrid rocks between adjacent mafic metavolcanic rocks and the monzonitic intrusion. Pyke (1970) interpreted this zone as a contaminated border zone of the monzonite intrusion. Outside of this zone, the monzonite is composed of plagioclase, potassium feldspar, hornblende, and traces of magnetite. The monzonite is generally medium-grained, weakly foliated, locally porphyritic (potassium feldspar, up to 1 cm) and contains between 30 to 60% ferro-magnesian minerals. The contaminated or hybrid border zone is very heterogeneous and characterized by variable amounts of potassium feldspar-phyric monzonite intermixed with medium-to coarse-grained pyroxene amphibolite (hornblende, pyroxene, magnetite) and monzonitic to tonalitic injections.

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[3] adapted from Hall and Houlé (2003)

Numerous dikes and sills intrude all supracrustal rocks, but mostly within Supracrustal Packages B and C. These small intrusive bodies and dikes display a range of compositions from monzonite to tonalite.

MT. LOGANO PORPHYRY

Mainly exposed in northeast Shaw Township, the Mt. Logano porphyry extends into northwest Carman Township. However, this extension of the Mt. Logano porphyry is essentially based on geophysical interpretation because of poor exposure in this part of the township. This intrusion contains abundant quartz with lesser plagioclase phenocrysts in a very fine-grained buff-white matrix. In general, the intrusion is least deformed at its core with evidence of progressively more strain toward its margins where it is fissile and sericitized.

PROTEROZOIC ROCKS

Matachewan Swarm[4]

Weakly magnetic mafic dikes of the Paleoproterozoic Matachewan dike swarm intrude all of the above rock units. Exposures of Matachewan dikes are distinctive orange-brown, positive weathering, and commonly elongate parallel to the dike trend. These dominantly north-northwest-trending dikes are largely undeformed, unmetamorphosed and unaltered, with the exception of some epidote mineral growth observed on subhorizontal joint surfaces. A rare feature of these mafic intrusive rocks is the presence of green, plagioclase phenocrysts or glomerocrysts that range up to 8 cm across. The intrusions commonly follow pre-existing structures and zones of weakness, but are observed to bifurcate. In the map area, Matachewan dikes have been observed to be up to 40 m wide. These dikes are easily delineated between exposures using airborne geophysical data due to their distinctive magnetic signature and straight trends.

Abitibi Swarm[4]

Southwest-trending, Mesoproterozoic, Abitibi dikes crop out in the map area in several localities, but are relatively constrained to the southern part of Carman and north-western corner of Langmuir townships. These ophitic textured, olivine gabbro dikes weather readily, resulting in the presence of coarse orange sand around exposures. Abitibi dikes are typically 20 to 50 m wide. Similar to the Matachewan swarm, Abitibi dikes are weakly magnetic yielding distinctive geophysical trends.

Huronian Supergroup

Several outcrops of the Cobalt Group are observed in the southwestern part of Langmuir Township. These outcrops constitute the most northerly exposure known to date of the Huronian Supergroup (Pyke 1970). Two main facies were observed in this area: 1) matrix-supported (average of 30% clasts) sandy conglomerate, unsorted, no layering, and polygenic rounded clasts (granitoids, chert, quartz, mafic to felsic volcanic rocks); 2) medium-green argillite strongly foliated with locally up to 5% rounded polygenic clasts. These sedimentary facies are interpreted to be a part of the Gowganda Formation.

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[4] adapted from Hall and Houlé (2003)

GEOCHRONOLOGY

In the past 2 years, a collaborative effort has been undertaken between the Ontario Geological Survey (OGS) and the Greenstone Architecture Project of the Discover Abitibi Initiative to improve the coverage of U/Pb geochronological data in the Shaw Dome area. The goals of this new geochronological work are

1. To establish stratigraphic frame work of the Shaw Dome area based on absolute age and regional bedrock mapping;
2. To constrain the age of the komatiitic volcanism and the nickel mineralization in the Shaw Dome area.

Previous Geochronological Samples

1. Felsic volcanic rock (footwall to Langmuir Mine #2; *see* Figure 7.1, sample 1) – 2708±2 Ma (Barrie and Corfu 1999).
2. Felsic volcanic rock (southeast Langmuir Township; *see* Figure 7.1, sample 2) – 2724±1.5 Ma (Barrie and Corfu 1999).

Barrie and Corfu (1999) suggested the presence of a reverse or thrust fault between their 2 samples in this specific area to explain the older age obtained toward the outside of the Shaw Dome structure. This interpretation has implications on the stratigraphy and the mineral potential of this area. This area is geologically complex because of the very poor exposure, but the recent bedrock mapping does not support this interpretation. However, new geochronological data will help to clarify this issue.

3. Gabbro (central Deloro Township; *see* Figure 7.1, sample 3) – 2707±3 Ma (Corfu et al. 1989). This gabbroic unit is a part of more primitive ultramafic to mafic intrusion located in the central part of Deloro Township.
4. Conglomerate (northern part of Deloro Township; *see* Figure 7.1, sample 4) – 2682±4 Ma and 2669±7 Ma (Ayer et al. 2003). This unit constitutes a small sliver of Timiskaming assemblage within the Tisdale assemblage.

New Geochronological Data

5. Felsic volcanic rock (Supracrustal Package A) is located in the eastern part of Shaw Township near the contact with Supracrustal Package C (*see* Figure 7.1, sample 5). This sample, collected in 2003, is an aphyric felsic to intermediate metavolcanic rock with several amygdules. The preliminary results on this sample yielded an age of 2727±6 Ma (M.A. Hamilton, Jack Satterly Geochronology Laboratory, University of Toronto, personal communication, 2004). This age confirms the previous hypothesis (Pyke 1982) that the central part of the Shaw Dome structure is indeed part of the Deloro assemblage.
6. Quartz-feldspar porphyry from the Mt. Logano intrusion is located in the northeast corner of Shaw Township (*see* Figure 7.1, sample 6). This quartz porphyry contains abundant quartz phenocrysts with lesser plagioclase in a very fine-grained buff matrix. The preliminary age for this sample is 2689±1.4 Ma (M.A. Hamilton, Jack Satterly Geochronology Laboratory, University of Toronto, personal communication, 2004). This new datum provides the age of one of the largest porphyritic intrusions in the region, which is indistinguishable from the age of numerous gold-associated porphyries in the Timmins camp (Ayer et al. 2003; MacDonald, Piercey and Hamilton, this volume).

7. Intermediate volcaniclastic rock within Supracrustal Package B is located in the central part of Eldorado Township at the Redstone Mine (*see* Figure 7.1, sample 7: geochronology currently in progress). This metavolcanic rock is the footwall of the main mineralization at the Redstone Mine (R zone). This is an intermediate to felsic volcaniclastic rock containing plagioclase fragments and quartz amygdules. It is anticipated this age will provide a minimum age for the nickel mineralization at Redstone and will also allow comparison with the age of 2708±2 Ma (Barrie and Corfu 1999) obtained for the footwall to the nickel mineralization at Langmuir Mine #2.
8. Intermediate epiclastic rock within Supracrustal Package B or C is located in the central part of Langmuir Township (*see* Figure 7.1, sample 8: geochronology currently in progress). This rock is a thin horizon of matrix-supported volcaniclastic rock and contains polygenic fragments within a siliceous matrix. This epiclastic unit is intercalated between 2 komatiite units with spinifex-textured zones. Based on the present bedrock mapping, this area (*see* Figure 7.1, samples 1 and 2) is believed to be part of the same supracrustal package B rather than 2 different packages as was suggested by the previous geochronological results (Barrie and Corfu 1999). The age of this sample will help to better understand the stratigraphic and structural evolution in this area.

MINERALIZATION

Numerous types of mineral deposits and occurrences are present in Carman and Langmuir townships including gold, nickel, copper, barite, and platinum group elements. Other commodities, such as silver, iron, zinc and asbestos, have drawn the attention of mineral explorationists to the Shaw Dome over the past 80 years.

Gold Mineralization

Presence of gold mineralization is identified in several localities in Carman and Langmuir townships. However, most of the gold properties in the map area are located in Carman Township (*see* Table 7.1). Lode-gold mineralization is associated with a wide range of lithologies, but especially with iron formation, quartz veins, or felsic intrusive rocks.

Gold associated with felsic intrusive rocks is very limited in this area, but has been reported in old assessment files. The mineralization is reported to occur with disseminated pyrite in a felsic or porphyry dike intruding the supracrustal rocks. However, this type of mineralization was not observed because diamond-drill core was unavailable as the drilling was completed in the 1960s. The reported gold values are anomalous, but not generally high (0.1 ounce per ton gold, MDI42A06NE00040 (OGS 2002)).

Gold mineralization associated with quartz veins within the metavolcanic rocks is very limited in the map area, but is also reported in old assessment files from work done in Carman Township. A more common association, but still limited, is the presence of quartz ± carbonate veins in the metavolcanic rocks and adjacent felsic intrusive bodies. The veins are generally massive and surrounded by haloes of sericite and carbonate alteration. The associated intrusions range from granitic to syenitic in composition. Finely disseminated sulphide minerals, mainly consisting of pyrite, are generally found in both the quartz-carbonate veins and in the felsic dikes.

The most prospective association for gold mineralization in the map area is with iron formations. First of all, numerous oxide and sulphide iron formations are present in the map area and contain disseminated pyrite and pyrrhotite. Secondly, one past producer (Carshaw–Malga Mine) is located nearby and exhibits the same style of mineralization. Most of the gold mineralization that is found in this area seems to be associated with sulphidization of the oxide iron formation that occurred during the injection of quartz ± carbonate veins (Photo 7.1).

Table 7.1. Summary of mineral properties in the mapping area and their main commodities (compiled by the Timmins Resident Geologist Office in South Porcupine from assessment files).

	Carman Township	Langmuir Township
Past Producer with Reserve	0	1
Past Producer without Reserve	0	1
Prospect with Reserve	0	2
Occurrence	8	15
Discretionary Occurrence	3	3
Main Mineralization	Au, Ni-Cu	Ni-Cu, PGE, brt, Au

Abbreviations: Au, gold; brt, barite; Ni-Cu, nickel-copper; PGE, platinum group elements

Magnesite Mineralization

Several occurrences of magnesite are found in the Shaw Dome area including the Canadian Magnesite deposit (south-central Deloro Township: owned by Globex Exploration Minerals); the Allerston deposit (southwestern Whitney Township); and another Globex Exploration property in northeastern Adams Township.

No known occurrence of magnesite was previously recognized in the map area. However, several exposures of weakly to highly carbonatized ultramafic rocks were recognized during the present bedrock mapping. This intense pervasive magnesite alteration is located in southwest Carman Township.

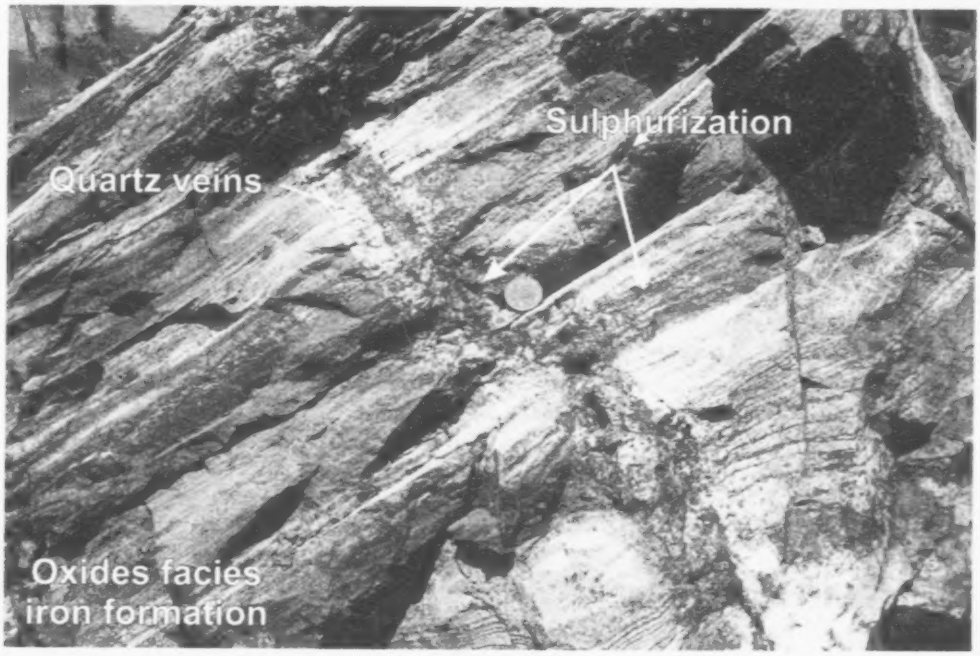

Photo 7.1. Bands of sulphurization by pyrite in an oxide iron formation in Carman Township; for location, *see* Figure 7.2.

Transformation of ultramafic rocks into magnesite-bearing rocks occur progressively (Kretschmar and Kretschmar 1986):

Dunite/peridotite →	**Serpentinite**	**Talc/magnesite**	**Magnesite/talc**
Magnetite veins	*Magnetite/asbestos veins*	*Carbonate/talc veins*	*Quartz/carbonate veins*

This gradation of the alteration also coincided with a progressive destruction of the primary igneous textures of the ultramafic rocks. Most of these gradational steps were observed in this part of the map area. Once the alteration process has occurred it is difficult to recognize the original host rock. The distinctive amber magnesium and iron carbonate minerals (magnesite, siderite, and limonite) are closely associated with the introduction of quartz in complicated arrays of *en échelon* veins in many of these occurrences. Photo 7.2 shows a typical exposure of ultramafic rocks characterized by intense and pervasive magnesite replacement.

Komatiite-Associated Nickel-Copper-Platinum Group Element Mineralization

Nickel-copper (Ni-Cu)-platinum group element (PGE) mineralization is mainly associated with extrusive and/or intrusive ultramafic rocks. Komatiite-hosted deposits contain a variety of mineralization types (Lesher and Keays 2002; *see also* Houlé, Lesher and Hall 2003). The most prospective Ni-Cu-(PGE) mineralization in the Shaw Dome area is the stratiform basal and/or footwall type consisting of massive to disseminated sulphide mineralization occurring at or near the base of the peridotitic or dunitic komatiite units.

Several Ni-Cu-(PGE) mineral deposits and occurrences are known in the map area including Langmuir Mine #2, Langmuir Mine #1, McWatters and Galata prospects. However, the Galata prospect is the only komatiite-associated mineralization exposed at the surface (Photo 7.3). All the other deposits were identified by diamond drilling, a consequence of the high proportion of the thick overburden in the map area.

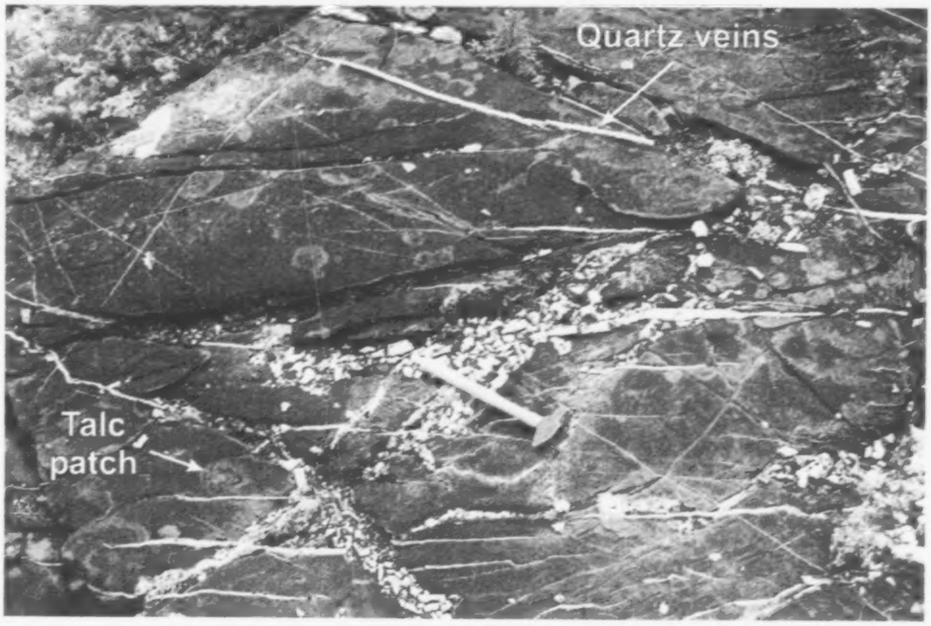

Photo 7.2. Pervasive carbonate alteration (magnesite) within ultramafic rocks in Carman Township; for location, *see* Figure 7.2.

Several factors are considered to be critical to the genesis of stratiform basal mineralization (Lesher and Keays 2002). These factors include:

1. the magma must be metal rich (e.g., komatiitic magma);
2. the magma must be sulphur undersaturated (e.g., komatiitic magma);
3. the magma must have access to an external sulphur source to achieve sulphur saturation (e.g., sulphide iron formation, sulphide-bearing graphitic argillite);
4. the presence of a dynamic magma system (e.g., olivine adcumulate, xenoliths);
5. and the presence of a physical trap (e.g., a depression).

Most of the known mineralization in the map area exhibits some or all of these critical features for the genesis of Ni-Cu-(PGE) mineralization.

RECOMMENDATIONS FOR EXPLORATION

Mining and exploration activities for Ni-Cu-(PGE) mineralization associated with komatiitic rocks have increased over the past few years in the Shaw Dome area, but have been relatively subdued for most other commodities. However, it should be noted that many of the rock types recognized in the area are similar to the rock units that host gold, nickel, copper, and PGE mineralization throughout the Abitibi Subprovince.

As Hall and Houlé (2003) pointed out, close spatial relationships between extrusive or intrusive ultramafic rocks (Supracrustal Package B and C) and sulphide-bearing iron formations (Supracrustal Package A and B) occur extensively along the margins of the Shaw Dome. The volume of komatiitic magma that interacted with an external sulphide source (the sulphide-bearing iron formation) is critical

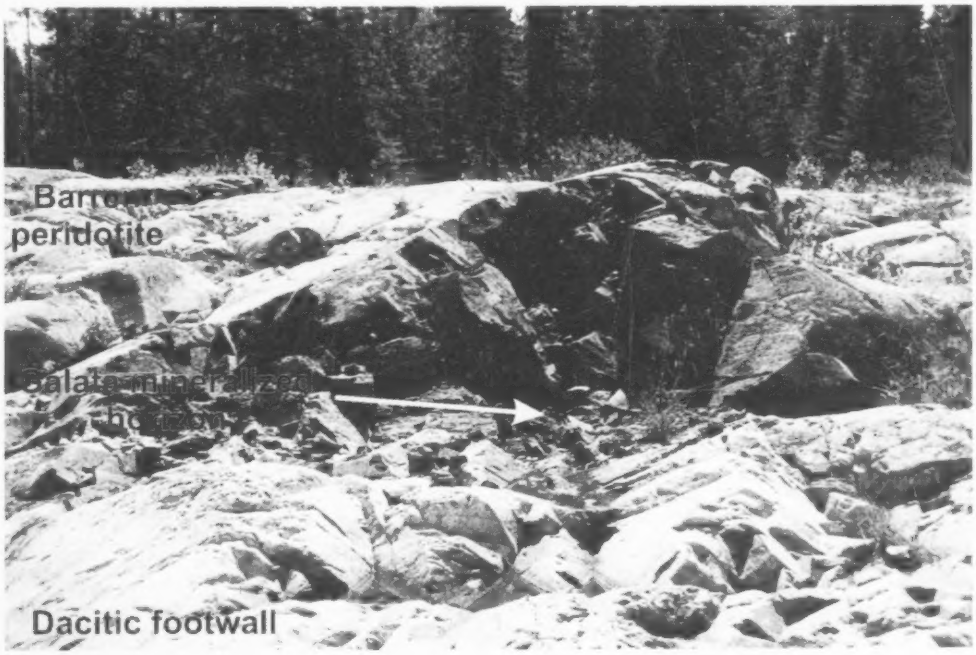

Photo 7.3. Ni-Cu-(PGE) mineralized horizon at the Galata prospect in Langmuir Township; for location, *see* Figure 7.2.

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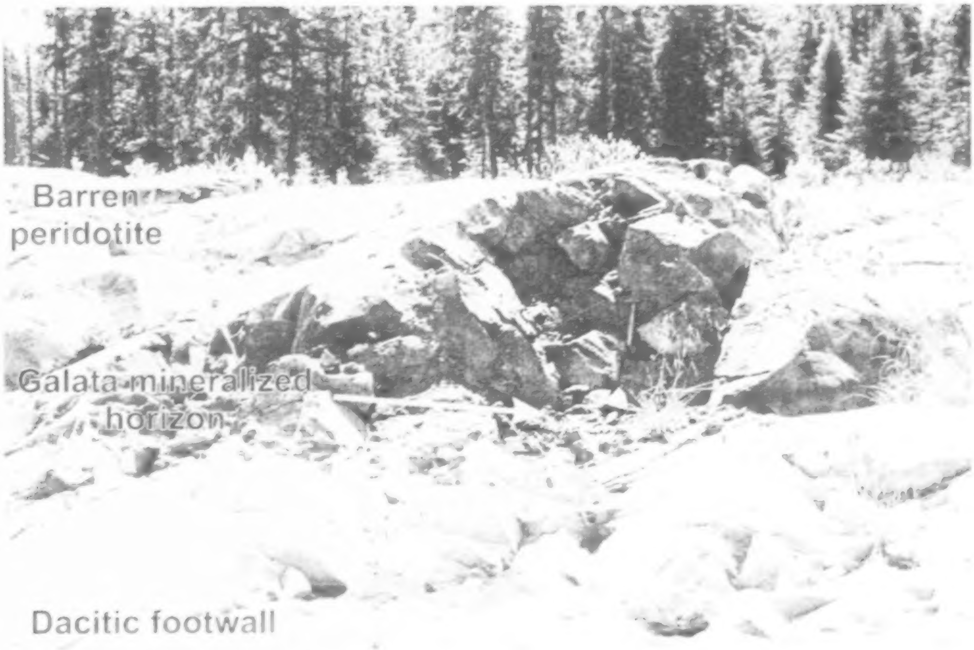

Photo 7.3. Ni-Cu-(PGE) mineralized horizon at the Galata prospect in Langmuir Township (for location, see Figure 7.2).

for komatiitic Ni-Cu-(PGE) mineralization. Abundant olivine cumulates indicates high volumes of magma, potentially sufficient to dissolve sulphur and precipitate sulphide minerals that carry the nickel, copper and platinum group elements. The combination of abundant olivine cumulate (i.e., high magma flux) and their proximity to sulphide-bearing iron formations (i.e., a sulphur source) results in an excellent exploration potential for finding more komatiite-associated Ni-Cu-(PGE) deposits in the map area.

Hall and Houlé (2003) also observed that numerous gold occurrences in the Shaw Dome demonstrate that gold mineralization is present south of the Porcupine–Destor deformation zone. Only a limited amount of exploration focussing on gold mineralization has been carried out in this part of the Timmins camp over the last 20 years. The association between gold and iron formation is well established. There is an abundance of iron formation in the map area that has not been fully tested for the presence of gold mineralization. Furthermore, some evidence of sulphidation, recognized as a critical mechanism to gold precipitation (e.g., MacDonald and Fyon 1986), has been observed in oxide iron formation in the southwestern corner of Carman Township. This type of mineralization is very similar to what was described at the Carshaw–Malga Mine, and therefore merits further investigation.

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8. Project Unit 04-006. Precambrian Geology and Mineral Potential of the Opikeigen Lake Area

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INTRODUCTION

The Precambrian Geoscience Section, Ontario Geological Survey (OGS) conducted bedrock mapping, at a scale of 1:20 000, in the Opikeigen Lake area of northwest Ontario. This mapping project is the first phase of an on-going project to map the Fort Hope greenstone belt in co-operation and partnership with the Eabametoong First Nation.

Operation Treasure Hunt airborne geophysical surveys (2003a, 2003b, 2003c) of the Fort Hope greenstone belt have indicated a more complicated geology than is delineated on the existing geology maps (Prest 1942; Thurston and Carter 1970; Wallace 1974, 1977, 1978a, 1978b). The volcano-sedimentary rocks of the belt and associated shear zones in the region are known to host gold mineralization (Wallace 1978c). Rare-element granitic pegmatites occur in association with felsic plutons in the region. Operation Treasure Hunt lake sediment geochemistry studies (OGS 2001) identified gold, rare-element and base metals anomalies in the area that may indicate the presence of more gold mineralization, mineralization associated with mafic to ultramafic rocks and with volcanogenic massive sulphide deposits.

Wallace (1974, 1977, 1978a, 1978b) previously mapped the Opikeigen Lake area and the Wottam Lake area to the west at a scale of 1:31 680. These areas represent the best exposed and most stratigraphically complete suite of rocks known in the Fort Hope greenstone belt. As such, this was considered the best area to begin the mapping of the belt.

The goals of this project are

1. To refine lithologic boundaries.
2. To clarify structural relationships.
3. To delineate and map volcano-stratigraphic associations and determine their relative ages, contact relationships and geochemical clans.
4. To determine what areas have the greatest potential for economic mineral deposits.
5. To ascertain which felsic pluton(s) the rare element-hosting pegmatites are genetically associated with.
6. To delineate what structures (if any) control gold mineralization.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.8-1 to 8-11.

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REGIONAL SETTING

The Fort Hope greenstone belt is located in the eastern part of the Uchi Subprovince of the Superior Province. The Uchi Subprovince is a 600 km long belt of volcano-sedimentary rocks that hosts the world-class Red Lake gold deposits as well as the Pickle Lake and Rice Lake gold mining camps. The Fort Hope greenstone belt is spatially constrained by plutonic and gneissic terranes that give the belt its wedge shape, flared to the west and narrowing to the east. To the north lies the plutonic North Caribou terrane of the Berens River Subprovince and to the south are the plutonic and metasedimentary rocks of the English River Subprovince (Stott and Corfu 1991). Figure 8.1 summarizes the regional geologic setting of the Fort Hope greenstone belt.

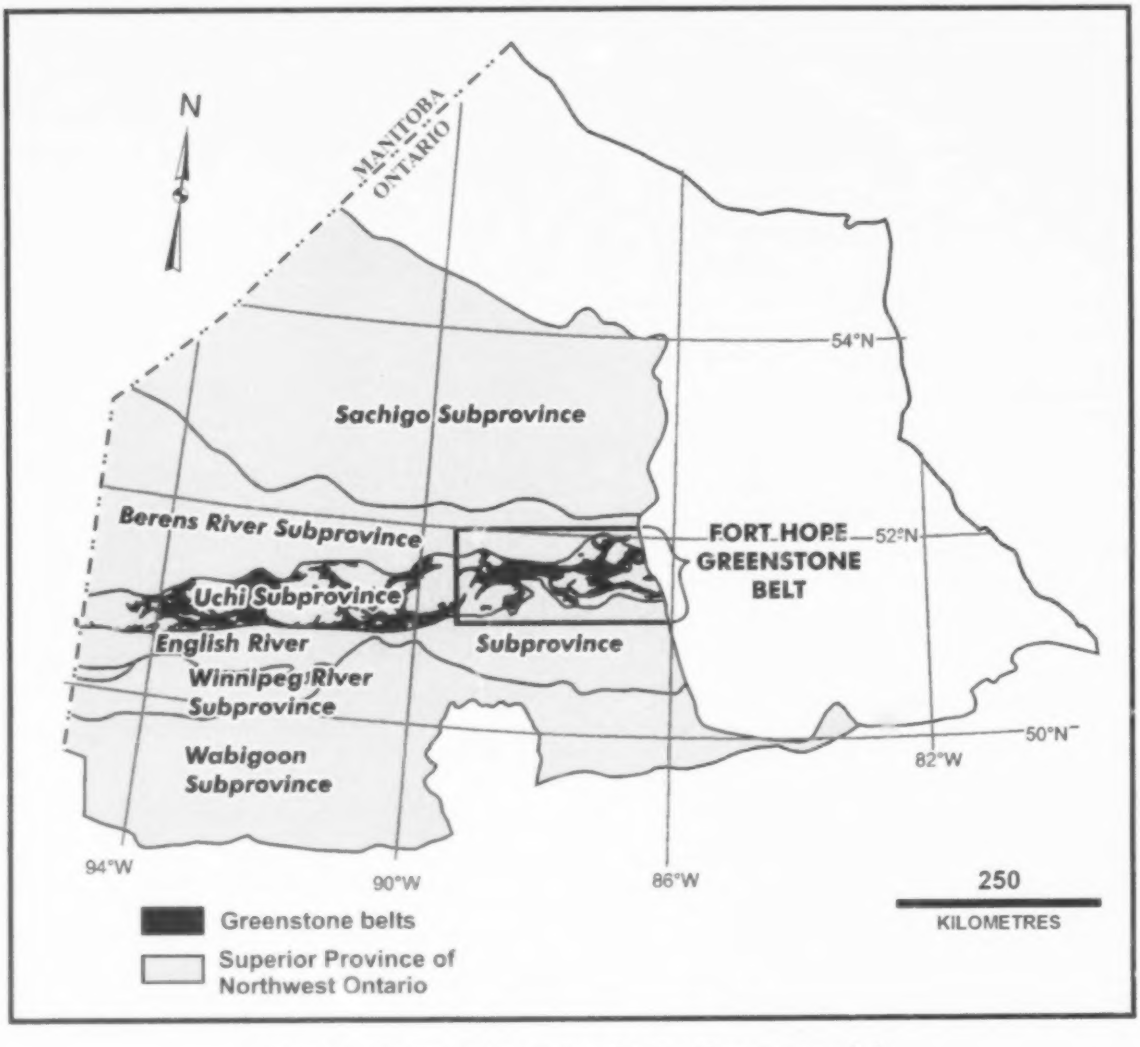
N
MANITOBA
ONTARIO
54°N
Sachigo Subprovince
Berens River Subprovince
52°N
FORT HOPE GREENSTONE BELT
Uchi Subprovince
English River
Subprovince
Winnipeg River Subprovince
50°N
82°W
Wabigoon Subprovince
94°W
90°W
86°W
250
KILOMETRES
■ Greenstone belts
□ Superior Province of Northwest Ontario

Figure 8.1. Regional geologic setting of the Fort Hope greenstone belt.

PRELIMINARY MAP

Prior to the beginning of the field season, all available regional information was assessed and a preliminary geological interpretation map was created (Figure 8.2). The map was used to focus mapping efforts on areas of complexity, to verify the geophysical interpretation of the geology and to target those areas where existing geology maps are at variance with other geoscience data.

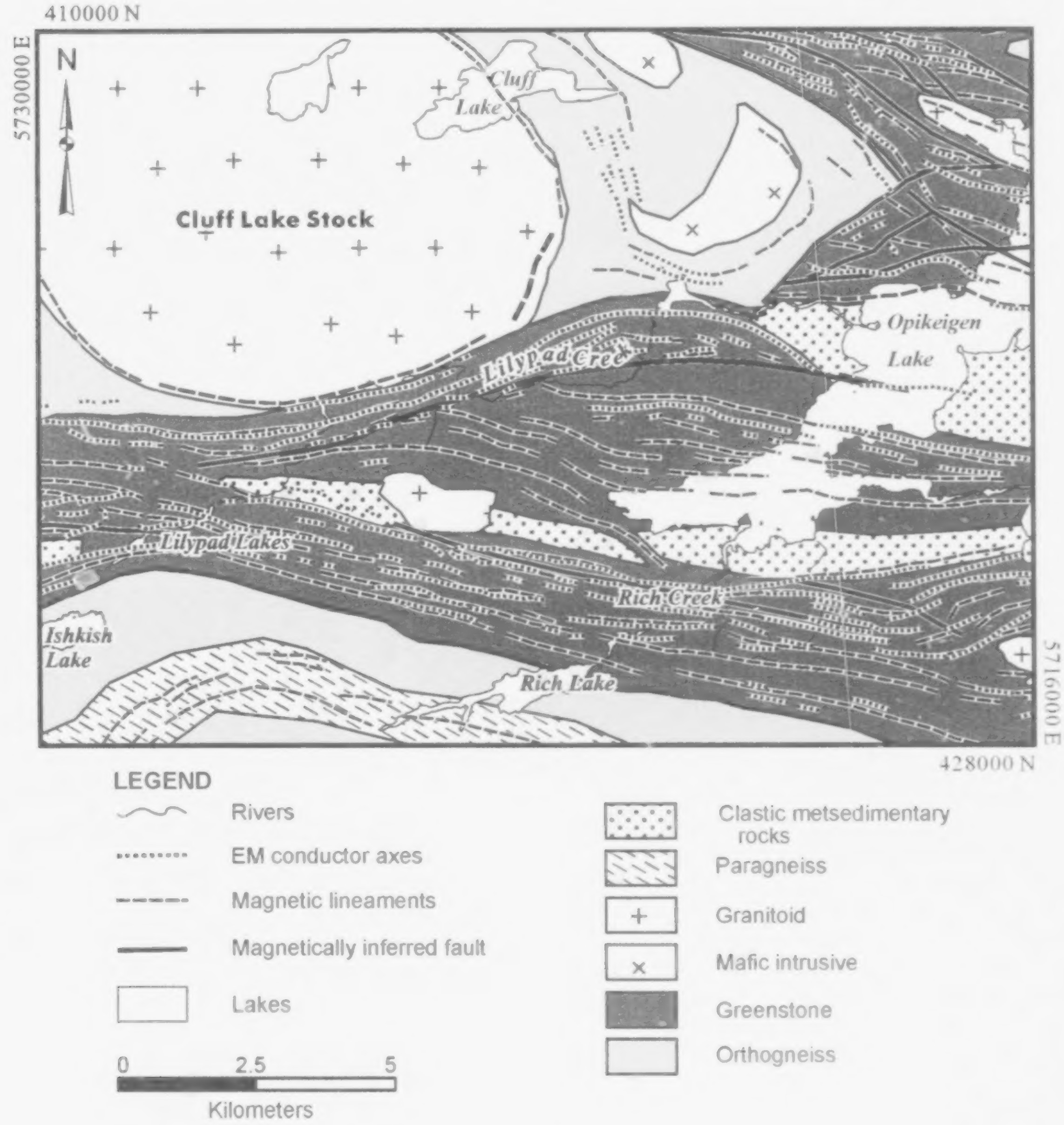
410000 N
5730000 E
N
Cluff Lake
Cluff Lake Stock
Opikeigen Lake
Lilypad Creek
Lilypad Lakes
Rich Creek
Ishkish Lake
Rich Lake
5716000 E
428000 N
LEGEND
Rivers
EM conductor axes
Magnetic lineaments
Magnetically inferred fault
Lakes
0
2.5
5
Kilometers
Clastic metsedimentary rocks
Paragneiss
Granitoid
Mafic intrusive
Greenstone
Orthogneiss

Figure 8.2. Preliminary geological interpretive map.

Loosely based on a process developed by the New South Wales Geological Survey, various data sets were georeferenced and compiled using geographic information system (GIS) software. The data included published bedrock geology maps, lake sediment geochemistry, airborne geophysics, topography, aerial photography, LANDSAT satellite imagery, Quaternary geology and administrative boundaries. A team of specialists was assembled to jointly assess and interpret the data.

GEOLOGY

The oldest rocks of the map area are the felsic, mafic, intermediate and mixed metavolcanic and clastic and chemical metasedimentary rocks that comprise the Fort Hope greenstone belt. Mafic, porphyritic intermediate, porphyritic felsic and pegmatitic felsic dikes as well as felsic to intermediate and small mafic plutons intrude all supracrustal rocks. All of the rocks of the area exhibit a great spectrum of metamorphic and deformational overprints, which gives them all a range of characteristics.

Mafic Metavolcanic Rocks

Chlorite schist, chlorite-amphibole schist and amphibole gneiss characterize the mafic metavolcanic rocks. Rare exposures display recognizable volcanic features. These include massive flows, pillows and flow-top breccias and pillow breccias. No tuffs or other pyroclastic textures were observed in the mafic metavolcanic rocks. However, this may simply be the result of metamorphism and deformation having obscured these features.

Both massive flow and pillowed mafic metavolcanic rocks are aphyric, medium green weathering and dark green on fresh surfaces. The thickness and any internal characteristics of the flows were not identified in the rare exposures that preserved recognizable flows. Pillows are relatively small with aspect ratios ranging from 20 × 10 cm to 170 × 50 cm in cross-section. Selvages are thin (1 to 6 cm), dark, negative weathering and may contain pillow fragments. Pillow selvages are typically more penetratively foliated than the pillows themselves, and the foliations wrap around the pillows following the selvages.

Chlorite schist is typically soft, fine-grained, equigranular with pronounced foliations easily identified on the outcrop surface. Medium green on the weathered surface and dark green on the fresh surface, these rocks do not react to dilute hydrochloric acid (HCl). Chlorite-amphibole schist is similar to the chlorite schist, but somewhat coarser grained, harder and darker on both fresh and weathered faces. The amphiboles are typically hornblende, but in close proximity to felsic pegmatites may be holmquistite (a lithium-bearing amphibole displaying a bluish or purple hue).

Gneissic amphibolite derived from mafic metavolcanic rocks is heterogeneous, with positive and negative weathering, discontinuous bands on the outcrop surface. These bands are leucocratic and melanocratic, respectively. The heterogeneity of this rock type may reflect a primary heterogeneity resulting from volcanic textures such as pillows, breccias and tuffs. This heterogeneity was useful in distinguishing amphibolitized metavolcanic from metamorphosed intrusive rocks. This rock type is locally garnet rich.

Felsic Metavolcanic Rocks

Felsic metavolcanic rocks exhibit a range of both primary and secondary characteristics. Primary textures observed include aphyric, quartz-phyric, feldspar-phyric, quartz- and feldspar-phyric, amphibole-phyric and amphibole- and feldspar-phyric. This spectrum reflects a compositional variation from truly felsic through intermediate compositions. Massive, lapilli-tuff, crystal-lapilli tuff, tuffs and *in situ* breccias encompass the textures observed. Well-preserved, relatively unmetamorphosed, felsic to intermediate metavolcanic rocks are rare in the map area. Typically, the felsic to intermediate metavolcanic rocks are quartz-sericite phyllites to schists; locally, these rocks display gneissic textures. Thin (10 to 80 cm) felsic to intermediate horizons are interbedded with clastic metasedimentary rocks.

Intermediate and Mixed Metavolcanic Rocks

An east-striking package of intimately layered metavolcanic rocks of varied compositions is identified within the southern belt of metavolcanic rocks in the map area. Rocks of this package range from felsic through mafic with intermediate compositions predominating. Mafic and felsic horizons range in thickness from 20 cm to 5 m, whereas the intermediate horizons range up to 20 m in thickness. The metamorphic character of these rocks varies from phyllitic chlorite- and sericite-bearing to garnet- and amphibole-bearing straight gneisses. The intimate compositional variation of this package allows the correlation of these rocks despite the spectrum of metamorphic overprint. This package provides a useful stratigraphic marker.

Iron Formation

Thin horizons of oxide-bearing, cherty iron formation occur in 3 distinct associations in the map area: 1) within mafic metavolcanic strata; 2) within large, mafic, metavolcanic xenoliths or rafts in the S-type gneissic pluton in the southern extent of the map area; and 3) within clastic metasedimentary strata in proximity with the southern margin of the Cluff Lake Stock. Observed iron formation horizons are less than 2 m thick. However, an 8 m thick horizon is reported to occur in the northeast corner of the map area (Wallace 1977) associated with mafic metavolcanic rocks. Another 8 m thick horizon is reported associated with metasandstones south of the Cluff Lake Stock (Wallace 1974). Black, positive weathering magnetite laminae are 0.5 to 2 cm thick. Grey, slightly negative weathering chert to siliceous argillite range in thickness from 0.5 to 4 cm. These iron formations have pronounced magnetic expression on airborne geophysical maps that allow them to be traced across the map area despite their limited exposure.

Clastic Metasedimentary Rocks

Metamorphosed, interbedded sandstones and siltstones to shales are exposed in the southern half of the map area. These rocks are intimately associated with the metavolcanic rocks and iron formation. The metasandstones were originally arkosic to wacke in composition. These rocks locally contain staurolite, sillimanite, and garnet and are phyllitic to gneissic in texture. The metamorphic overprint is generally strongest in the more southerly exposures of the metasedimentary rocks. Two weakly gossanous metasandstones are exposed roughly on strike with each other north of the Lilypad Lakes and south of the Cluff Lake Stock. One gossan is associated with iron formation, whereas the other is associated with (interpreted) felsic metavolcanic rocks. Reported exposures of conglomerate (Wallace 1977) are reinterpreted to be pseudoconglomerate (Hall 1990). The pseudoconglomerate forms when sandstone is subjected to post-depositional strain, giving the sandstone the appearance of a monomictic conglomerate.

Mafic Intrusive Rocks

Medium- to coarse-grained, locally porphyritic mafic intrusive rocks occur throughout the map area. Concordant to sub-concordant mafic sills and dikes range in width from 10 cm to 20 m. To the northwest of Opikeigen Lake, mafic intrusive rocks are exposed 500 m across strike thereby comprising the largest mafic intrusive body of the map area. Mafic dikes exposed in southern Opikeigen Lake are amphibolite and garnet-amphibolite gneiss. Contact relationships, the presence of rare, angular felsic xenoliths and their relatively homogeneous nature allows these rocks to be distinguished from the amphibolitized mafic metavolcanic rocks which they intrude.

Intermediate Porphyritic Intrusive Rocks

Rare exposures of grey, negative weathering, hornblende-porphyritic dikes occur in the outcrops north of the Lilypad Lakes. Ranging in width from 8 cm to 1 m, these dikes intrude the supracrustal rocks, and were everywhere observed to be concordant with the main fabric in the rocks.

Quartz-Feldspar Porphyritic Intrusive Rocks

Felsic porphyritic dikes of varied character occur across the southern half of the map area intruding supracrustal rocks. White to pale yellow-grey weathering, these dikes are up to 150 m wide and display a range of characteristics. Phenocrysts of quartz, feldspar, and quartz and feldspar are locally very abundant (30%). Quartz phenocrysts are typically grey, round and positive weathering and range in diameter up to 1.2 cm. Feldspar phenocrysts are white weathering, lath-shaped crystals that range up to 5 mm in length. One dike, observed near Rond Lake in the southeast region of the map area, consists of a marginal phase of quartz-feldspar porphyry with a core of quartz porphyry. Where phenocrysts are rare and contact relationships are covered, it can be difficult to distinguish these rocks from the felsic metavolcanic rocks. However, the intrusive rocks generally display less pronounced deformational fabric than the metavolcanic rocks, and this criteria was used to assign the lithologic designation while in the field.

Felsic Pegmatitic Intrusive Rocks

In the vicinity of the Lilypad Lakes supracrustal rocks, felsic porphyritic dikes and felsic plutonic rocks host felsic pegmatitic intrusions. These white weathering dikes are predominantly coarse-grained, quartz-albite in composition with tourmaline, spodumene, lepidolite, beryl and pollucite present locally. Brown, negative weathering, metasomatic haloes 2 to 20 cm wide are the result of the introduction of boron to the country rocks (F.W. Breaks, OGS, personal communication, 2004). Dikes locally appear undeformed, are folded in S-shaped configurations, and display fault offsets. This seeming inconsistency is herein interpreted to reflect the rheologically competent nature of these coarse-grained rocks that results in the dikes only locally expressing strain. Breaks and Tindle (this volume) offers a more complete description of these intrusive rocks.

S-type Felsic Plutonic Rocks (Orthogneiss)

A well-exposed body of gneissic to massive, felsic plutonic rock occupies the southern extent of the map area. Coarse-grained to pegmatitic, foliated to massive quartz-monzonite to granite intrude pink orthogneiss in a *lit-par-lit* configuration. Abundant xenoliths of clastic metasedimentary rocks, metavolcanic rocks and iron formation characterize the northern exposures of this plutonic body. These range in size up to 20 m wide. Trains of dismembered iron formation xenoliths may be traced for several kilometres within the pluton using a combination of the Operation Treasure Hunt airborne magnetic data (OGS 2003b, 2003c) and outcrop observations. The contact between this body and the metamorphosed supracrustal rocks that host abundant dikes of the felsic pluton is gradational and, therefore, arbitrary.

Cluff Lake Stock

Two exposures of the Cluff Lake Stock (Wallace 1977) were visited during the course of bedrock mapping. The southern exposure is coarse-grained, equigranular, white weathering, hornblende-rich (30%) tonalite to diorite containing abundant small metasedimentary xenoliths. Narrow (3 cm) pegmatitic dikes cut the tonalite to diorite and have no metasomatic haloes. The exposure visited in the north-central region of the pluton was sampled for U/Pb geochronology. This coarse-grained granodiorite weathers light pink, is dark orange-pink with abundant (>15%) hornblende on the fresh surface, displays a weak, non-penetrative foliation and is cut by small, pink, coarse-grained granitic dikes.

STRUCTURE

A thorough structural analysis of the area has yet to be attempted, however numerous field observations of a structural nature were made during the course of bedrock mapping and are summarized below:

- The dominant foliation trend in the map area is steeply dipping and east striking in the south and steeply dipping and west striking in the north. North of Lilypad Creek, west of Opikeigen Lake outcrops display a west-northwest to northwest foliation trend.
- There is a broad spectrum of intensity of the main foliation in the area. However, in general, the fabrics are more pronounced in the southern half of the map area than they are to the north.
- Stratigraphic facing was locally determined based on graded bedding in the metasedimentary rocks and pillows in the mafic metavolcanic rocks. Facing was interpreted to both north and south. These data will aid the interpretation of map-scale folds.
- Outcrop-scale, Z-shaped, tight to isoclinal folds are present in the supracrustal rocks north of the Lilypad Lakes. The axial planes of these folds are parallel to or slightly counter-clockwise to the main foliation.
- The Lilypad Lakes pegmatite dikes locally display outcrop-scale, S-shaped, tight to close folds. The axial planes of these folds are generally at a high angle to the main foliation, however, they display a great range of orientations.
- Horizontal crenulations are present on some of the more penetratively foliated exposures, particularly the metasedimentary rocks south of Lilypad Creek and the Lilypad Lakes.
- Z- and S-shaped kinks were observed in strongly foliated rocks throughout the map area.
- An east-striking mylonite zone can be traced along the southern shore of the Eabamet River. A similar structure is present to the north of the Lilypad Lakes that is tentatively interpreted to be the continuation of the same zone.
- A series of 3 north- to north-northeast-trending faults in the Lilypad Lakes area correspond to two present on Wallace's map (1977), and a third not represented that is 1.5 km to the east. Offsets in stratigraphy and the aforementioned mylonite zone are interpreted to be the result of these sinistral brittle faults.

MINERALIZATION

Known mineral occurrences in the Opikeigen Lake area fall into 3 commodity types: gold, tungsten and rare-elements (Be, Cs, Ga, Li, Nb, Rb and Ta). The locations of these mineral occurrences are plotted on Figure 8.3.

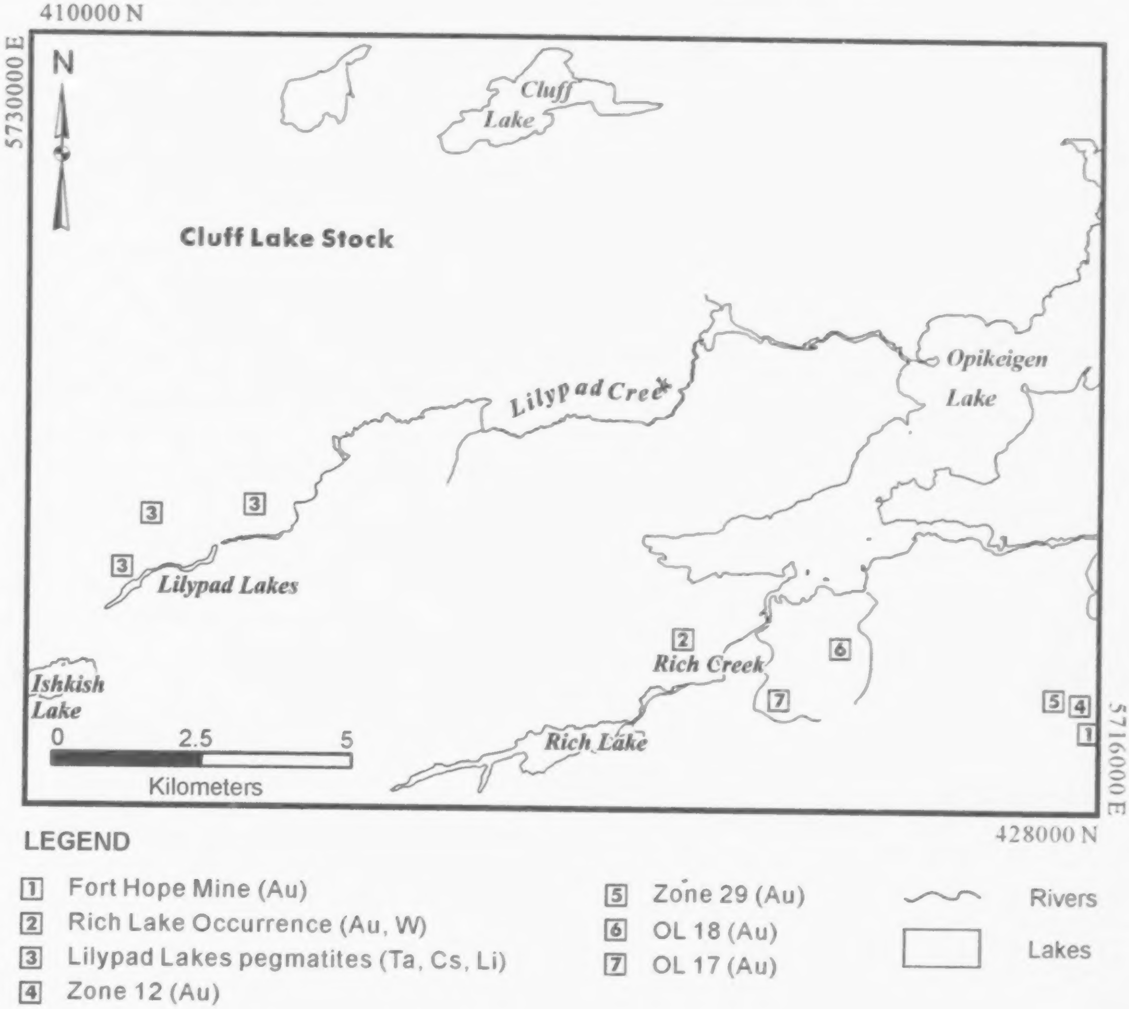
410000 N
5730000 E
N
Cluff Lake
Cluff Lake Stock
Lilypad Creek
Opikeigen Lake
3
3
3
Lilypad Lakes
2
Rich Creek
6
7
Ishkish Lake
0
2.5
5
Kilometers
Rich Lake
5
4
1
5716000 E
428000 N
LEGEND
1 Fort Hope Mine (Au)
2 Rich Lake Occurrence (Au, W)
3 Lilypad Lakes pegmatites (Ta, Cs, Li)
4 Zone 12 (Au)
5 Zone 29 (Au)
6 OL 18 (Au)
7 OL 17 (Au)
Rivers
Lakes

Figure 8.3. Location of mineral occurrences in the Opikeigen Lake area. Abbreviations: Au, gold; Cs, cesium; Li, lithium; Ta, tantalum; W, tungsten.

Table 8.1. Summary of gold showings in the Opikeigen Lake area.

Showing Name	Host Lithology	Local Structures	Mineralization Type	Associated Minerals	Wall-Rock Alteration
Fort Hope Mine	Massive and pillowed mafic metavolcanic rocks	Northeast- and northwest-trending quartz veins	Quartz and quartz-carbonate vein-hosted		Silicification
Rich Lake Occurrence	Tuffaceous mafic metavolcanic rocks	West-southwest-trending, boudinaged quartz veins	Quartz and quartz-biotite-chlorite (Zebra) veins	Scheelite	
Zone 29 (Diamond drill-hole only)	Tuffaceous felsic to intermediate metavolcanic rocks	East-northeast-trending shear zone	Shear-hosted	Pyrite	Silicification Sericitization
Zone 12 (Diamond drill-hole only)	Mafic metavolcanic, metagabbroic and quartz-feldspar porphyritic dikes	Northeast- and east-northeast-striking brittle shear zones with sinistral offset	Quartz and quartz-sulphide veins in shear zones	Silver Molybdenite	Silicification Carbonatization
OL-87-17 (Diamond drill- hole only)	Tuffaceous, mafic metavolcanic rock	Shear zone	Shear-hosted	Pyrite Magnetite	
OL-87-18 (Diamond drill-hole only)	Chloritic tuff in felsic metavolcanic rocks			Pyrite Pyrrhotite	

Gold

The map area is located in the Uchi Subprovince which hosts the Red Lake and Pickle Lake gold camps. In 1927, prospectors discovered gold mineralization in quartz veins cutting mafic metavolcanic rocks approximately 2 km west of the northwest end of Eabamet Lake (Prest 1942; Wallace 1977). A 38 m shaft was sunk with 101 m of lateral development at what is known as the Fort Hope gold mine (Wallace 1977, 1978a). This find launched a small staking rush in the area that resulted in the discovery of numerous other gold showings (Burwash 1929). Exploration activities have continued sporadically since the initial discovery in 1927. Table 8.1 summarizes the general characteristics of the gold showings that have been reported in the Opikeigen Lake area.

Rare-Elements

Pegmatitic rocks that are genetically related to evolved S-type granitoid plutons are the primary economic host of rare-element minerals. Granitoid pegmatites were observed in the southern half of the map area. Where encountered, these rocks were sampled for analysis. The results of these analyses will be published when they become available. Known rare-element mineralization occurs in the Lilypad Lakes pegmatites where recent exploration by Avalon Resources has been conducted. A more detailed description of the Lilypad Lakes pegmatites is provided by Breaks (Breaks and Tindle, this volume).

Tungsten

Scheelite occurs in gold-bearing quartz veins at the Rich Lake occurrence. Composite (Thurston and Carter 1970) and grab (Wallace 1977, 1978a) samples returned 0.65% and 0.50% WO_3, and 0.80% and 1.50% WO_3, respectively.

Nickel-Copper-Platinum Group Elements

Numerous exposures of mafic intrusive rocks were encountered through the course of this project. These were sampled and are being analyzed for nickel, copper and platinum group element (PGE) content. The results of these analyses will be made public after they are returned.

RECOMMENDATIONS

Limited mining activities were conducted at the Fort Hope mine beginning in 1927. Numerous other gold occurrences (Table 8.1) are present in the map area. The land overlying most of these prospective areas of the map area are currently staked and exploration is progressing on these claims.

Rare-element granitic pegmatites are exposed throughout the southern half of the map area and are present both east and west of the map area. Current economic factors, coupled with the size of these dikes, renders the known dikes sub-economic at this time. However, the abundance of the pegmatites, high grades of tantalum and cesium in these dikes and their widespread distribution would suggest that there was a large system at work that generated these pegmatites. It is possible, given the extensive cover in the area, that economically viable rare-element pegmatites are present in this area waiting to be discovered.

The structural complexity, presence of mineral occurrences, the as yet untested rock types with economic potential coupled with the relatively under-explored nature of the area suggest that further investigation into the rocks of the Fort Hope greenstone belt is warranted.

ACKNOWLEDGMENTS

This project has benefited from the able and enthusiastic assistance of Mark Waters, John Ray Meeseetawageesic and Rodney Ostamas. Fred Breaks offered tremendous insight into the pegmatitic rocks at Lilypad Lakes. Desmond Rainsford collaborated on the preparation of the preliminary map and in writing a description of the process for this article. Mark Smyk, John Mason, Gerry White, Greg Stott (Ontario Geological Survey) and Jim Garber (Landore Resources) all provided valuable insight into the area. Martha Papah and Brad Yesno from the community of Eabametoong expedited our communication and mapping activities and helped staff my crew. Chris Papah, Bradley Meeseetawageesic, Zack Slipperjack and Quincy O'Keese helped with field work while we were based in the community of Eabametoong. Julie Chartrand drafted the figures rapidly yet with an eye to detail and accuracy as well as aesthetics. The staff of Leuenberger Air Service cheerfully and professionally provided the logistical support that this type of project relies on so intimately. They went above and beyond. Finally, the Eabametoong First Nation community was both supportive and welcoming to me and to my project.

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9. Project Units 02-007 and 04-018. Paleomagnetic Studies of Proterozoic Mafic Dikes, Eastern Wabigoon and English River Subprovinces

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INTRODUCTION

This project is an ongoing collaborative partnership, initiated in 2002, between the Ontario Geological Survey and the University of Toronto to investigate the age, geochemistry and paleomagnetism of Proterozoic mafic dike swarms. Work is being completed on dike swarms in the eastern Wabigoon Subprovince (Halls and Stott 2003; Stott and Halls 2002; Davis and Stott 2003) and continuing into the eastern part of the English River Subprovince. Our investigation of the dike swarms will provide insight into their continuation under the James Bay Lowlands where a spatial correlation of diamondiferous kimberlite pipes with the presence of north-and northwest-striking dikes can be discerned (Stott and Halls 2002; Stott 2003).

During 2004, 48 oriented samples for paleomagnetic study were collected from 5 dike locations with the prime objective of discriminating the various mafic dike swarms east and northeast of Lake Nipigon. Selected dikes have been sampled for geochronology: Ar/Ar analyses of hornblende by J. Hanes, Queen's University and U/Pb analyses of baddeleyite by D.W. Davis, Jack Satterly Geochronology Laboratory, University of Toronto. Whole rock geochemical analyses of samples collected from all of the mafic dikes are being conducted at the Geoscience Laboratories, Sudbury. An open file report summarizing the results and interpretations of this work is being prepared for release in 2005.

EXPERIMENTAL PROCEDURES

The map of the region west of Lake Nipigon (Figure 9.1) shows the location of all dikes studied since the start of the project in 2002. Those that have been sampled this year are labelled in bold type. In addition, 2 sites (LL17, LL18) were obtained along Highway 17 near Hemlo and White River, southeast of the area shown in Figure 9.1. Samples, oriented using both magnetic and sun compasses, were obtained from chilled margins where fine-grained magnetite preserves a higher coercivity primary remanence that is more resistant to subsequent change. Most samples were field drilled as cores 2.45 cm in diameter, but a few were obtained as blocks, especially finely jointed samples from dike margins. At least 7 samples were collected from each site. All cores were cut into 2.45 cm lengths and the natural remanent magnetization (NRM) of each specimen was measured on a modified DIGICO spinner magnetometer. The specimens were then subject to alternating field (AF) demagnetization using a Schonstedt single-axis instrument in order to remove low coercivity, secondary components. The data were then analyzed using Principal Component Analysis, with visual aids supplied by stereonet and vector plots (Kirschvink 1980).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.9-1 to 9-4.

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RESULTS

The paleomagnetic results are summarized in Table 9.1. Three sites (LL17, LL19 and LL21) yielded remanence directions typical of the 2.45 Ga Matachewan dike swarm. The two westernmost results (LL19 and LL21) can be combined with the Lake Nipigon data set in Table 11.1 of Halls and Stott (2003). For all sites with $\alpha_{95} \le 15°$, the new Matachewan results give Declination = 188.5°, Inclination = - 20.2°, k, precision parameter = 73, $\alpha_{95} = 4.5°$, and N, the number of sites = 15. All 15 Matachewan dikes have R polarity suggesting that, by the time of the subsequent N polarity epoch, dike injection had shrunk back towards the focal region of the swarm (south of Sudbury) in the waning stages of Matachewan igneous activity.

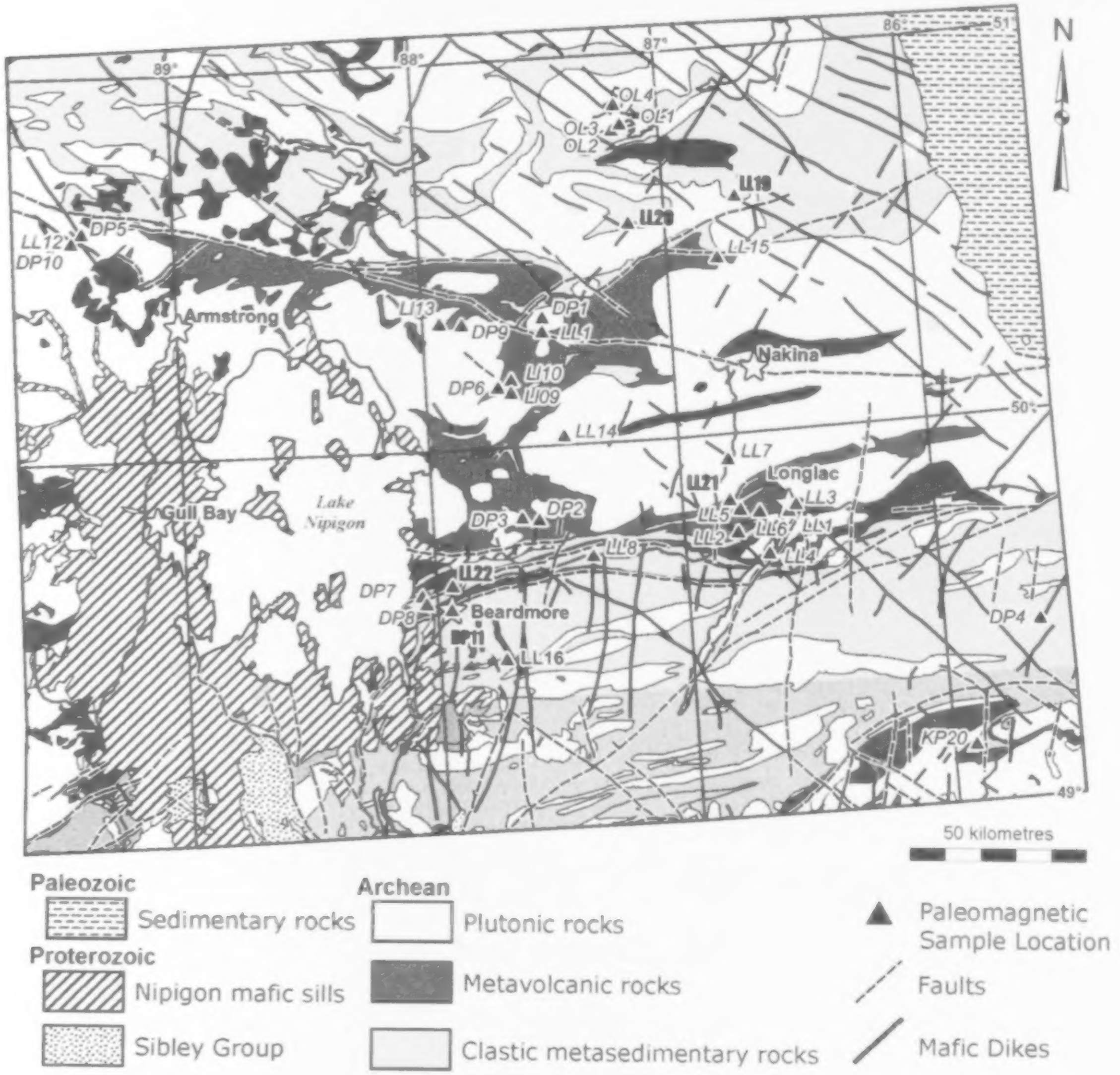
89°
88°
87°
86°
51°
N
OL4
OL1
OL3
OL2
LL19
LL20
LL15
LL12
DP5
DP10
Armstrong
LL13
DP1
DP9
LL1
LL10
DP6
LL09
Nakina
50°
LL14
LL7
LL21
Longlac
LL3
LL5
LL2
LL6
LL1
LL4
Gull Bay
Lake Nipigon
DP3
DP2
LL8
LL22
DP7
DP8
Beardmore
DP11
LL16
DP4
KP20
49°
50 kilometres
Paleozoic
Sedimentary rocks
Proterozoic
Nipigon mafic sills
Sibley Group
Archean
Plutonic rocks
Metavolcanic rocks
Clastic metasedimentary rocks
Paleomagnetic Sample Location
Faults
Mafic Dikes

Figure 9.1. Locations of Proterozoic mafic dikes sampled east and north of Lake Nipigon during 2002 to 2004. Samples collected in 2004 are highlighted in bold.

Table 9.1. Paleomagnetic results for samples of Proterozoic mafic dikes collected in 2004.

Site	Latitude (N)	Longitude (W)	Width (m)	Strike	Declination	Inclination	n[N]	k	α_{95}
MATACHEWAN									
LL17	48°36.655′	85°19.571′	40	310°	192.6°	–16.5°	5[7]	26	14.0°
LL19	50°36.664′	86°42.700′	40	305°	185.3°	–29.3°	11[12]	94	4.7°
LL21	49°49.813′	86°49.081′	25+	310°	196.5°	–30.2°	8[10]	65	6.9°
MARATHON or BISCOTASING									
LL20	50°33.368′	87°09.172′	65+	050°	275.2°	77.4°	8[8]	163	4.3°
NIPIGON (Keweenawan)									
LL22	49°38.894′	87°56.492′	40	010°	120.9°	–80.4°	3[11]	25	25.0°
DP11	49°36.434′	87°57.104′	30+	350°	119.8°	–74.3°	5[7]	120	7.0°
KEWEENAWAN (?)									
LL18	48°41.469′	86°00.398′	26	280°	286.8°	25.2°	8[13]	47	8.2°

Notes: **Width** and **Strike** are, respectively, the thickness and azimuthal orientation of the dike; **Declination** and **Inclination** define the direction of the Remanent magnetization; **n** is the number of samples in a site used to determine the paleomagnetic direction; **N** is the total number of samples measured; **k** is precision parameter; and $\boldsymbol{\alpha_{95}}$ is the radius of the 95% confidence circle about the mean direction. Samples with unacceptable directions were either lightning-struck or had generally low coercivity remanences with scattered directions.

A comparison of paleomagnetic directions in Matachewan dikes on either side of the Kapuskasing Structural Zone (KSZ)—a major fault-bounded belt of uplifted crust that trends south-southwest from James Bay—suggests that the western half of the Superior Province has rotated counter-clockwise approximately 10 to 20° with respect to the eastern half across the KSZ and that the amount of rotation increases to the west (Bates and Halls 1991). The Lake Nipigon data represent the farthest west that Matachewan dikes have been sampled, but the mean direction is not significantly different from that found 200 km farther east in the Hornepayne area (Bates and Halls 1991). Although some differential rotation may have occurred in that part of the Superior Province within approximately 400 km west of the KSZ, at greater distances, the Archean terrane appears to have behaved as a rigid block. The similar pole positions of the Fort Frances dikes (2076 Ma) in Ontario and the Cauchon Lake dike swarm (2092 Ma) in Manitoba (1000 km away to the north) would support this conclusion (Halls 1986; Halls and Heaman 2000).

Two sites (DP11 and LL22) yielded paleomagnetic directions that are typical of Keweenawan sills and sheets in the Lake Nipigon area. Both dikes are north trending and, in fact, could be part of the same intrusion. Another north-trending dike at site DP8 is suspected of being Keweenawan (Halls and Stott 2003). This, together with northwest-trending Keweenawan diabase at site LL16, means that a northwest- to north-trending dike set may be the underlying feeder system for at least some of the sills and sheets.

Of the two remaining sites, one site (LL20) has a signature similar to the Marathon dike swarm signature, although it could belong to the older Biscotasing dike swarm, recently identified in the region (Halls and Davis 2004). The final site (LL18) is of interest because it has a west-northwest-directed, intermediate-down remanence direction that is similar to that found in normal polarity Keweenawan dikes (1094 Ma). It is likely that it is a feeder of the normal polarity part of the Coldwell complex (circa 1100 Ma), which occurs along strike of the dike about 20 km to the west. The dike has a spectacular array of host rock xenoliths along its northeast margin.

CONCLUSION

Some progress has been made towards one of the stated aims of the project (*see* Stott and Halls 2003), namely, to identify feeder systems for the Keweenawan sills and sheets. The trend of the Logan–Nipigon intrusive suite is generally north, which has prompted speculation that a north-trending aulacogen associated with early development of the Keweenawan Central North American Rift system is present. The north trend of suspected Keweenawan dikes in the region southeast of Lake Nipigon lends credence to this supposition.

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10. Project Unit 03-011. Discrimination of Archean Domains in the Sachigo Subprovince

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INTRODUCTION

This note serves to introduce a new project designed to better outline the broad tectonic subdivisions of Archean crust in the northern Sachigo Subprovince (Figure 10.1). As currently accepted in northern Manitoba and near the Manitoba–Ontario provincial boundary, the Sachigo Subprovince incorporates at least two or three terranes north of the North Caribou terrane including the region underlying the Hudson Bay Lowlands. Terrane boundaries have been generally positioned between the North Caribou, Oxford–Stull terranes and Northern Superior Superterrane (e.g., Percival and Helmstaedt 2004, with some modifications that reflect our present level of uncertainty, e.g., Figure 10.2). This project will focus on U/Pb age determinations and Nd isotopic characteristics of plutonic rocks in the eastern Sachigo Subprovince, including basement underlying the Hudson Bay and James Bay lowlands, in order to extend the tectonic boundaries eastward. This work is also a contribution to the Trans-Hudson–Superior Margin Metallotect project, a collaborative federal–provincial study, between the Geological Survey of Canada and respective provincial geological surveys. (For further details on this broader, collaborative project, please see the links on the Internet web page http://nrd.nrcan.gc.ca/nrd_t14/index_e.aspx?aricleid=298.)

PROBLEM

The large region of Archean crust north of Uchi Subprovince in Ontario has been commonly labelled the Sachigo Subprovince (e.g., Card and Ciesielski 1986). This has served as a general regional subdivision, but masks the presence of important terranes and their tectonic assemblages. Speculation about its subdivision into tectonic terranes of contrasting crustal ages began with the publication of the *Geology of Ontario* (e.g., Thurston, Osmani and Stone 1991). Results of recent mapping (e.g., Stone and Hallé 2002), geochronology (e.g., Davis and Stott 2001) and isotopic work (e.g., Skulski et al. 2000), arising from a federal–provincial NATMAP collaboration, has resulted in a generally agreed upon framework of major terranes. The Sachigo Subprovince is thought to be subdivided into at least 3 fault-bounded terranes: 1) the 3.0 Ga North Caribou terrane in the south, 2) a juvenile 2.73 to 2.72 Ga Oxford–Stull terrane in the central Sachigo and 3) the reworked 3.6 Ga crust of the Northern Superior Superterrane in the north (Corkery et al. 2001; Skulski et al. 2000). However, much of the evidence for the subdivision of the Sachigo Subprovince is based on work in Manitoba and near the Manitoba–Ontario provincial border (e.g., Corkery et al. 2001; Stone and Hallé 2002). In the eastern part of the subprovince, there are insufficient data regarding the ages of crustal protoliths and its extension under the lowlands. This tectonic subdivision and the location of the northern boundary of the North Caribou terrane become more tenuous farther east in Ontario. Only one age determination has been made previously in eastern Sachigo Subprovince, east and north of the North Caribou greenstone belt. This result is from detrital zircons of a quartz-rich wacke in the Wunnummin greenstone belt (*see also* sample 12 on OGS 1991;

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.10-1 to 10-8.

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Davis 1989), which was interpreted to indicate that the sediments were derived from a single source of about 2965 Ma.

Consequently, there is a need to greatly improve our knowledge base of the geochronological and isotopic signature of the eastern Sachigo Subprovince and adjacent lowlands of Ontario. This will help establish a regional tectonic subdivision across this broad portion of the Superior Province and correlate it more effectively with possible on-strike equivalents in Quebec and Manitoba.

As a contribution towards rectifying this knowledge gap, we have collected a widely distributed set of rock samples for geochronological and isotopic analyses. These samples are mainly granitoids from outcrops in the eastern Sachigo Subprovince and from diamond-drill core of Archean bedrock underlying parts of James Bay and Hudson Bay lowlands (*see* Figure 10.2). Samples for geochronology and whole rock geochemistry have been obtained through the assistance of several exploration companies, notably De Beers Canada Exploration Inc., Wallbridge Mining Co. Ltd. and Spider Resources Inc., and from the MNDM Drill Core Library at the Resident Geologists office in South Porcupine.

OBJECTIVES AND METHODOLOGY

1. The primary objective of this project is to gather new geoscience information to enable us to confidently extend Archean tectonic boundaries—between the North Caribou, Oxford–Stull and Northern Superior superterranes—into the eastern part of Sachigo Subprovince and under the Paleozoic cover rocks of James Bay and Hudson Bay lowlands. This will be achieved by obtaining U/Pb zircon ages (SHRIMP) and Nd whole rock and Hf zircon isotopic (using laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS)) characterizations of Archean rocks collected from selected sites in the eastern Sachigo Subprovince and from diamond-drill core samples of basement rocks underlying the Paleozoic cover. Analytical work will be conducted at the Geological Survey of Canada facilities on a suite of 10 to 15 samples.

2. A secondary objective is to assess the record of movement along the Winisk River fault. There is some evidence from published geophysical aeromagnetic maps (Gupta 1991) that much of the movement might be Archean in age, based in part on the lack of offset of apparent Matachewan dikes of approximately 2446 Ma age that cross the fault. There also appears to be little evidence of subsequent transcurrent offset, owing to the apparent lack of offset in aeromagnetic patterns of other Proterozoic mafic dikes. However, this does not discount the possibility of episodes of vertical displacements that might coincide with post-Archean orogenic events at a distance from the Superior Province, including the Trans-Hudson Orogen. To examine the history of movement, some diamond-drill core samples of sheared felsic to intermediate plutonic rocks have been obtained from the Timmins Drill Core Library (03GRS-32, 33,34, Figure 10.3). These are being examined by N. Rayner to assess the feasibility of determining the timing of fault movement using accessory minerals, such as titanite, where there is a clear relationship to shearing. J. Hanes, Queen's University, is assessing the potential of using Ar/Ar geochronology of minerals in these fault samples.

3. A third objective is to assess the detrital geochronology of a suite of Ordovician–Silurian quartz-rich sediments that directly overlie the Archean basement, plus quartz arenites that occur within the Paleozoic stratigraphy from 2 widely separate diamond-drill hole sites. The purpose is to evaluate zircon provenance and shed some light on the nature of Phanerozoic epeirogenic movements, and compile a tectonostratigraphic framework.

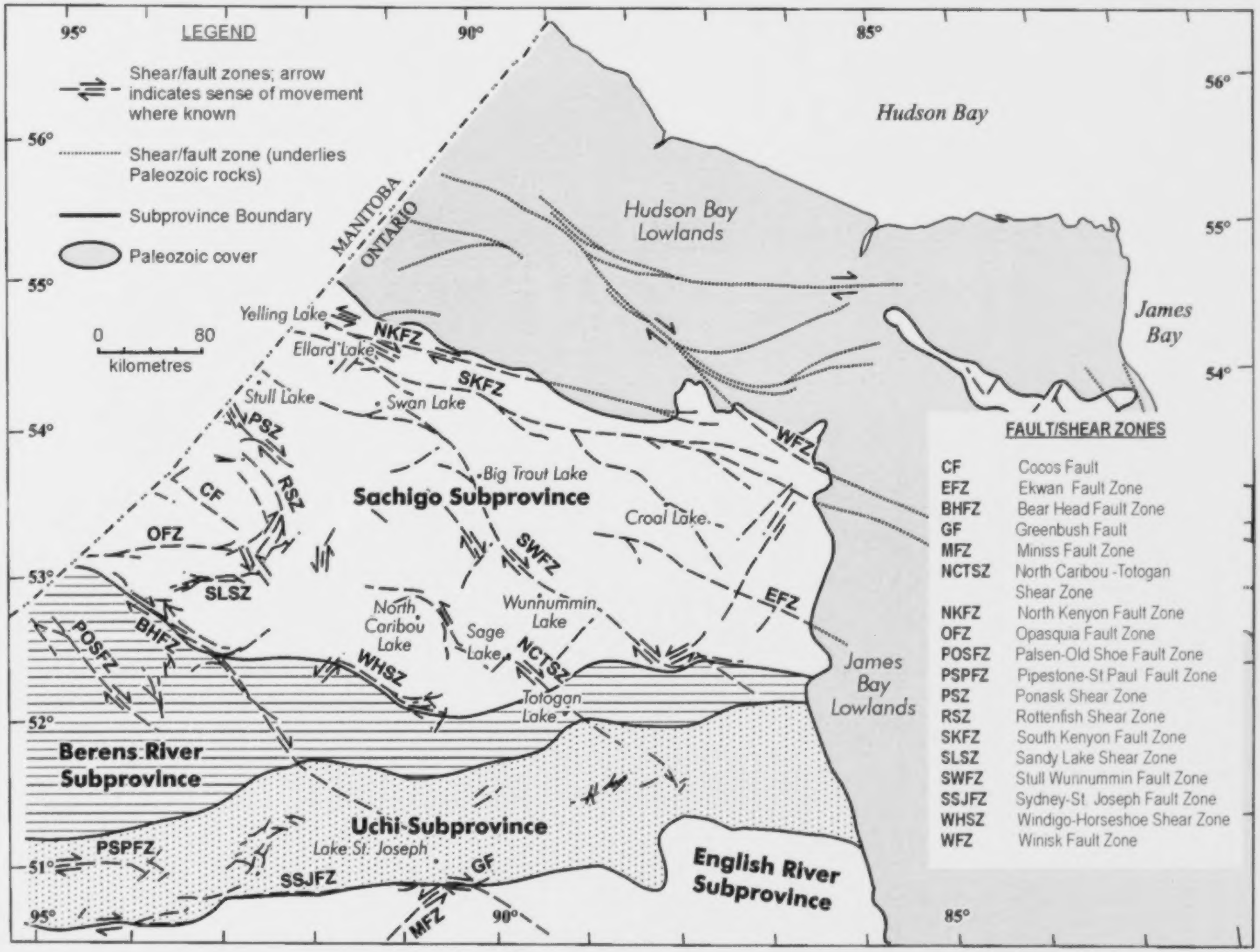

95°
90°
85°
56°
55°
54°
53°
52°
51°
LEGEND
Shear/fault zones; arrow indicates sense of movement where known
Shear/fault zone (underlies Paleozoic rocks)
Subprovince Boundary
Paleozoic cover
0
80
kilometres
Hudson Bay
Hudson Bay Lowlands
James Bay
James Bay Lowlands
MANITOBA
ONTARIO
Yelling Lake
Ellard Lake
Stull Lake
Swan Lake
Big Trout Lake
Croal Lake
North Caribou Lake
Sage Lake
Wunnummin Lake
Totogan Lake
Lake St. Joseph
Sachigo Subprovince
Berens River Subprovince
Uchi Subprovince
English River Subprovince
NKFZ
SKFZ
WFZ
PSZ
RSZ
CF
OFZ
SLSZ
BHFZ
POSFZ
WHSZ
SWFZ
NCTSZ
EFZ
PSPFZ
SSJFZ
GF
MFZ
FAULT/SHEAR ZONES
CF Cocos Fault
EFZ Ekwan Fault Zone
BHFZ Bear Head Fault Zone
GF Greenbush Fault
MFZ Miniss Fault Zone
NCTSZ North Caribou -Totogan Shear Zone
NKFZ North Kenyon Fault Zone
OFZ Opasquia Fault Zone
POSFZ Palsen-Old Shoe Fault Zone
PSPFZ Pipestone-St Paul Fault Zone
PSZ Ponask Shear Zone
RSZ Rottenfish Shear Zone
SKFZ South Kenyon Fault Zone
SLSZ Sandy Lake Shear Zone
SWFZ Stull Wunnummin Fault Zone
SSJFZ Sydney-St. Joseph Fault Zone
WHSZ Windigo-Horseshoe Shear Zone
WFZ Winisk Fault Zone

Figure 10.1. The Sachigo Subprovince bordered by other subprovinces and the Paleozoic cover rocks of the James Bay and Hudson Bay lowlands. This part of the Superior Province of northwestern Ontario has been further subdivided tentatively into terranes (*see* Figure 10.2). Major faults and shear zones are modified from Osmani and Stott (1988).

A SHRIMP detrital zircon study is being conducted on 2 quartz-rich clastic sedimentary units at the basement–Paleozoic cover contact from 2 deep diamond-drill holes (greater than 200 m) in widely separate parts of the lowlands. One sample (03GRS-26) is from a diamond-drill hole of Wallbridge Mining Co. in the Hudson Bay Lowlands and the other (03GRS-22) is just south of the Victor kimberlite pipe of De Beers Canada Exploration Inc. in James Bay Lowlands (*see* Figure 10.3). In conjunction with this, F.R. Brunton of the Sedimentary Geoscience Section, Ontario Geological Survey, is arranging for conodont analyses, supported by De Beers Canada Exploration Inc., to determine the age of the Ordovician–Silurian strata from a complete stratigraphic section provided by diamond-drill core from De Beers Victor kimberlite property. The first series of conodont samples from the Victor property establishes a Late Ordovician through Late Silurian age for the mixed siliciclastic-carbonate country rocks. A conodont alteration index (CAI) of 1 for all samples indicates that no significant thermal overprint of the Silurian carbonate-dominated system has occurred. Current work involves a detailed assessment of the relative ages of sedimentary lithoclasts within the Attawapiskat kimberlite pipes.

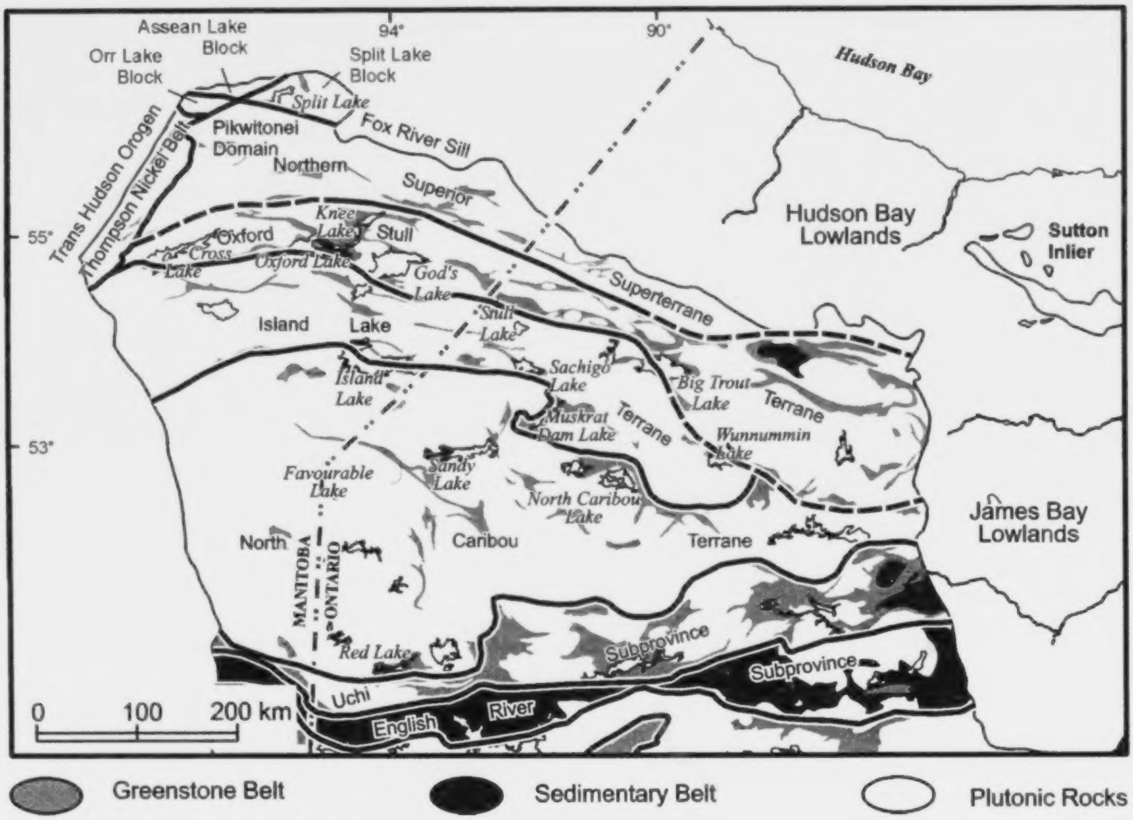

Assean Lake Block
94°
90°
Orr Lake Block
Split Lake Block
Hudson Bay
Split Lake
Trans Hudson Orogen
Thompson Nickel Belt
Pikwitonei Domain
Fox River Sill
Northern
Superior
Hudson Bay Lowlands
55°
Knee Lake
Stull
Oxford
Cross Lake
Oxford Lake
God's Lake
Sutton Inlier
Superterrane
Island
Lake
Stull Lake
Sachigo Lake
Island Lake
Big Trout Lake
Terrane
Muskrat Dam Lake
Terrane
Wunnummin Lake
53°
Favourable Lake
Sandy Lake
North Caribou Lake
North
Caribou
Terrane
James Bay Lowlands
MANITOBA
ONTARIO
Red Lake
Subprovince
Subprovince
Uchi
English
River
0
100
200 km
Greenstone Belt
Sedimentary Belt
Plutonic Rocks

Figure 10.2. One example of a subdivision of the Superior Province into terranes in northwestern Ontario and Manitoba (figure *modified from* D. Stone, Ontario Geological Survey, personal communication 2004), incorporating suggestions by others (e.g., Corkery et al. 2001; Skulski et al. 2000; Thurston, Osmani and Stone 1991). Greater confidence of the major subdivisions lies within Manitoba and near the Ontario–Manitoba border with increasing uncertainty eastwards across this region, reflecting the current distribution of geochronological and isotopic studies.

DISCUSSION

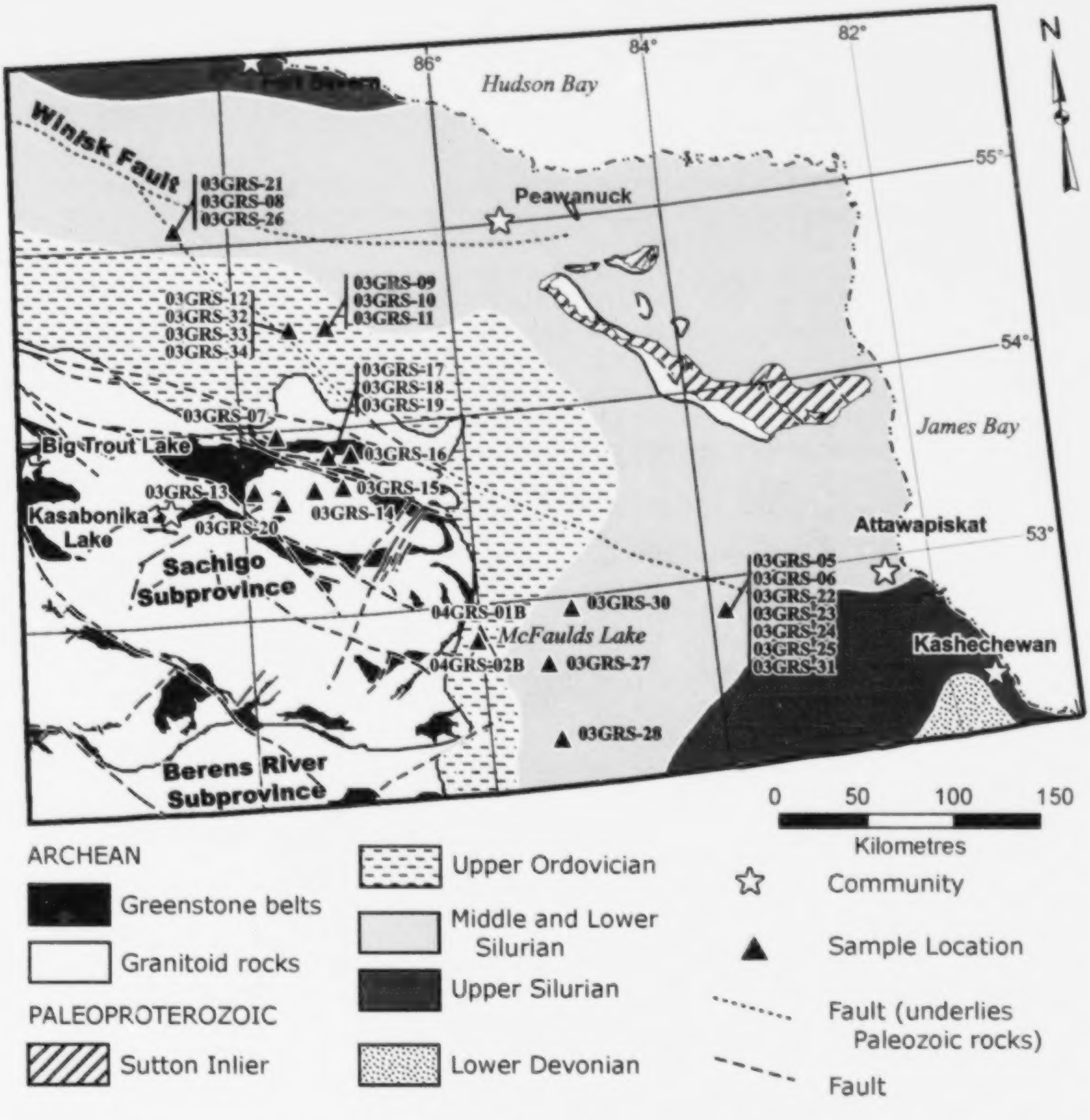
The attempt to shed greater light on the tectonic subdivisions of the Sachigo Subprovince is, in part, driven by the significant potential for various mineral deposits in this region. Exploration for diamond-bearing kimberlite pipes in Ontario has placed considerable attention on the thick Archean lithosphere in the vicinity of the James Bay and Hudson Bay lowlands. Major lithospheric breaks are of interest in diamond exploration and one of the fundamental boundaries in the Superior Province, beginning to be appreciated, is that between the Northern Superior Superterrane and the Oxford–Stull terrane. The Kenyon fault system is postulated, from work near the Ontario–Manitoba provincial border, to mark the boundary between these 2 terranes. There is a difference in interpretation between Skulski et al. (2000) and Stone and Hallé (2002) as to whether the North Kenyon fault or the South Kenyon fault, respectively, marks the boundary. The east extensions of these faults remain unclear and generally poorly exposed, but they appear to continue as separate fault systems under the James Bay Lowlands (Osmani and Stott 1988). What is also unclear is to what extent one of these faults continues to mark the boundary between the Oxford–Stull terrane and the Northern Superior Superterrane farther to the east. This project is intended to provide some insight on the eastward continuation of these boundaries.

Not all major dextral, transcurrent shear zones in the Sachigo Subprovince formed along fundamental tectonic boundaries. East- and southeast-striking faults (Osmani and Stott 1988) are broad, dextral right-handed transcurrent shear zones. The Stull–Wunnummin fault zone for example is over 3 km wide (Stott and Janes 1985), yet its southeast trend from the Big Trout Lake greenstone belt to the northern margin of the Wunnummin greenstone belt appears to cut across the Oxford–Stull terrane as we currently understand it. Only a portion of this fault zone might follow a major terrane boundary along the Wunnummin greenstone belt and accordingly provide a potential focus for kimberlite pipes and late tectonic, platinum group element-bearing mafic to ultramafic intrusions. Numerous gold occurrences, spatially associated with major and minor faults and shear zones, occur across the Sachigo Subprovince and deserve further investigation (Osmani and Stott 1988). For most occurrences, their relation to major terrane boundaries remains speculative until we obtain a much better understanding of the tectonic subdivisions across a broader portion of this subprovince.

One of the recent exploration attractions to this region is the discovery of Cu-Zn volcanic-hosted massive sulphide (VMS) deposits in the McFaulds Lake area, just inside the eastern edge of the James Bay Lowlands by Spider Resources Inc. with their partner KWG Resources Inc. The greenstone belt in which these deposits occur forms an east-closing arc that appears to extend discontinuously west towards the Kasabonika belt and southwest towards the Wunnummin greenstone belt (*see* Figure 10.2). Samples for age determinations and isotopic characterization of the dacitic host rock at McFaulds Lake (samples 04GRS-01B, 02B) were obtained through J. Burns, Senior Project Geologist, Spider Resources Inc. These samples complement a set obtained from diamond-drill core provided by N. Novak, Vice President Exploration, Spider Resources Inc. from several sites in the James Bay Lowlands. The intent here is to begin to determine if 1) this is a relatively young Archean greenstone belt and 2) whether the protolith of this region of Archean crust is dominantly Neoarchean.

The McFaulds greenstone belt shows a discontinuous correlation with the Kasabonika greenstone belt on geophysical aeromagnetic maps (Gupta 1991) and forms a linear belt that might contain not just one, but several, massive sulphide occurrences along its length. The current exploration activity in search of VMS deposits (Figures 10.3 and 10.4) is concentrated in the concave-shaped greenstone belt near McFaulds Lake. However, the distribution of VMS deposits in other greenstone belts gives some encouragement that similar deposits might occur within one tectonic assemblage along the length of this belt system extending from Kasabonika to the southeast.

For comparison, one could refer to the band-like tectonic assemblage (circa 2720 Ma), which is discontinuously preserved along the northern margin of the Wawa Subprovince from Shebandowan through Terrace Bay to the Manitouwadge greenstone belt (Corfu and Stott 1998). This assemblage contains numerous VMS occurrences and past producers along its length (*see* Figure 10.4). With this analogy and additional insight from geochronology and geochemistry, one could argue for increased investigation along the entire Kasabonika–McFaulds greenstone belt and its arcuate extension southwest towards the Wunnummin greenstone belt.



Fort Severn
86°
84°
82°
N
Hudson Bay
Winisk Fault
55°
03GRS-21
03GRS-08
03GRS-26
Peawanuck
03GRS-09
03GRS-10
03GRS-11
03GRS-12
03GRS-32
03GRS-33
03GRS-34
54°
03GRS-17
03GRS-18
03GRS-19
03GRS-07
James Bay
Big Trout Lake
03GRS-16
03GRS-13
03GRS-15
Kasabonika Lake
03GRS-20
03GRS-14
Attawapiskat
53°
Sachigo Subprovince
03GRS-05
03GRS-06
03GRS-22
03GRS-23
03GRS-24
03GRS-25
03GRS-31
04GRS-01B
03GRS-30
McFaulds Lake
Kashechewan
04GRS-02B
03GRS-27
03GRS-28
Berens River Subprovince
0
50
100
150
Kilometres
ARCHEAN
Greenstone belts
Granitoid rocks
PALEOPROTEROZOIC
Sutton Inlier
Upper Ordovician
Middle and Lower Silurian
Upper Silurian
Lower Devonian
Community
Sample Location
Fault (underlies Paleozoic rocks)
Fault

Figure 10.3. The distribution of rock samples and drill core samples in eastern Sachigo Subprovince and the adjacent lowlands. The geochronology and isotopic character of these samples are being analyzed to help extend the main terrane subdivisions into the eastern portion of Sachigo Subprovince. Unless specified in the text, the samples shown here are samples collected for basement characterization (objective 1).

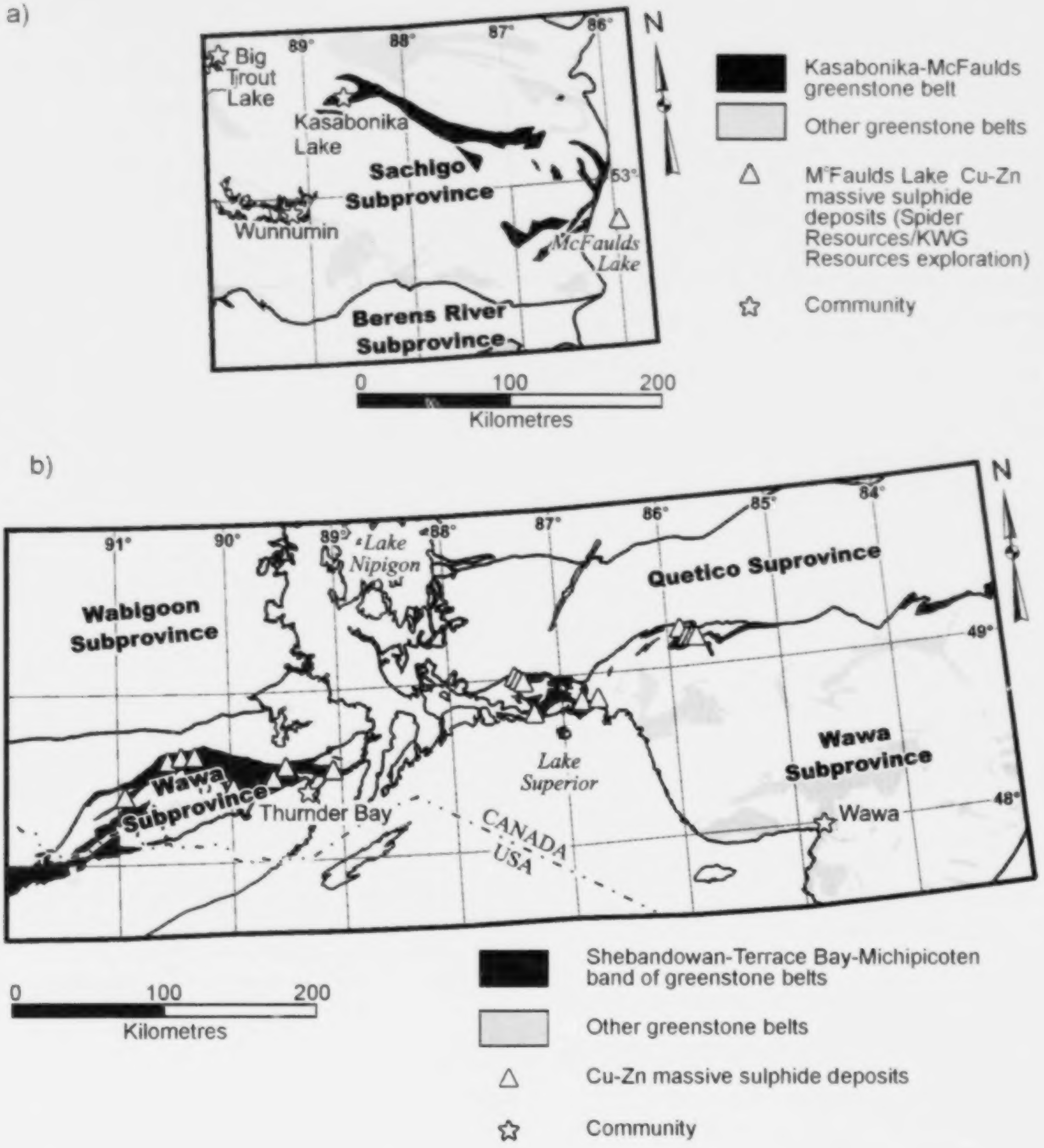

a)
N
89°
88°
87°
86°
53°
Big Trout Lake
Kasabonika Lake
Sachigo Subprovince
Wunnumin
McFaulds Lake
Berens River Subprovince
0
100
200
Kilometres
Kasabonika-McFaulds greenstone belt
Other greenstone belts
McFaulds Lake Cu-Zn massive sulphide deposits (Spider Resources/KWG Resources exploration)
Community
b)
N
91°
90°
89°
88°
87°
86°
85°
84°
49°
48°
Lake Nipigon
Wabigoon Subprovince
Quetico Suprovince
Wawa Subprovince
Thunder Bay
Lake Superior
CANADA
USA
Wawa Subprovince
Wawa
0
100
200
Kilometres
Shebandowan-Terrace Bay-Michipicoten band of greenstone belts
Other greenstone belts
Cu-Zn massive sulphide deposits
Community

Figure 10.4. a) The discontinuously preserved Kasabonika–McFaulds greenstone belt, which arcuately extends partly under the James Bay Lowlands, is the subject of exploration for Cu-Zn volcanogenic massive sulphide (VMS) deposits by several companies in the vicinity of McFaulds Lake. b) The discontinuously preserved Shebandowan–Terrace Bay–Manitouwadge greenstone belt highlighting the circa 2720 Ma tectonic assemblage that traces along the Wawa–Quetico subprovinces boundary and which contains numerous VMS deposits along its length. This band-like tectonic assemblage, populated with a chain of VMS deposits, encourages a comparative template for the VMS potential along the Kasabonika–McFaulds belt in Sachigo Subprovince.

ACKNOWLEDGMENTS

We thank several exploration companies for their assistance in obtaining rock samples from the Sachigo Subprovince and Hudson Bay Lowlands. In particular, we thank Don Boucher and his staff of De Beers Canada Exploration Inc., Doug Hunter of Wallbridge Mining Co. Ltd. and Neil Novak and James Burns of Spider Resources Inc. Ann Wilson, District Geologist at Timmins, provided valuable assistance in locating diamond-drill core and records from the lowlands.

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11. Project Unit 04-039. Rare-Element Granitic Pegmatites of the Fort Hope Field, North-Central Ontario

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INTRODUCTION

The Fort Hope pegmatite field, as named by Černý and Meintzer (1988), represents the fourth largest concentration of rare-element mineralization in the Superior Province of Ontario, after the Separation Rapids group, and the Georgia Lake and Dryden fields, respectively (Figure 11.1; Breaks, Selway and Tindle 2003a, 2004). This field comprises 32 rare-element occurrences, mostly in the Lilypad Lakes pegmatite group (Figure 11.2), that includes resource estimates (Avalon Ventures Limited 2001) for the Pollucite dike (340 000 tonnes averaging 0.037 weight % Ta_2O_5 and 2.29 weight % Cs_2O) and the Rubellite dike (800 000 tonnes averaging 0.032 weight % Ta_2O_5, equivalent to 567 000 pounds of Ta_2O_5).

The main purpose of the present work, which involved one week of field investigation, was to accrue bulk rock and mineralogical samples of the various pegmatite types and sub-types for chemical analysis and geochronology. The data derived from this study will augment the Ontario Geological Survey rare-element geochemical database as previous information stemming from government investigations on mineral and bulk chemistry from this area is non-existent. The mineral samples include amblygonite, apatite, columbite group, garnet group, lepidolite, muscovite, pollucite-analcime series, potassium feldspar, spodumene and the tourmaline group. Rubellite, the pink variety of elbaite (lithium-rich tourmaline), is rare in the Superior Province as a whole with only 2 known localities at the Tanco pegmatite (Selway, Černý and Hawthorne 2000) and in the Lilypad Lakes pegmatite group.

PREVIOUS INVESTIGATIONS

The Fort Hope area has witnessed a long history of geological and mineral exploration that commenced with reconnaissance mapping of Bell (1886, p.15-16) and later by Burwash (1929). Prest (1944) followed with 1:63 360-scale geological mapping and discovered 3 rare-element pegmatite occurrences with pink tourmaline, spodumene, lepidolite and fluorite that now constitute the Rubellite dike. More recent reconnaissance work was conducted by Thurston and Carter (1970) and succeeded by 1:31 680-scale geological mapping by Wallace (1977, 1978), who also examined the rare-element pegmatites in the Lilypad Lakes area and identified pollucite, amblygonite, cassiterite and scheelite.

Mineral exploration for rare-element pegmatites of the area commenced in 1956 by Standard Lithium Mines Corporation, who examined claims PA 27166 and PA 27168 (located on Map 2379, Wallace 1977) for its lithium potential by trenching and 12 diamond-drill holes totalling 968 m.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.11-1 to 11-9.

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R.J. Campbell (1962) followed with 3 diamond-drill holes, totalling 212 m, on pegmatites from the same claims. During 1979 to 1981, the Tantalum Mining Corporation of Canada conducted a large survey to establish the tantalum potential of the pegmatite group. Lithogeochemistry, electromagnetic and magnetic ground geophysical surveys were followed by 52 diamond-drill holes totalling 5367 m. Avalon Ventures Limited (2001) carried out a comprehensive survey from 2001 to 2002 to further evaluate the tantalum and cesium potential of the pegmatites. The work involved detailed geological and structural mapping, lithogeochemical, gravity and ground geophysical magnetic surveys, mineralogical analysis, and 2786 m of diamond-drilling in 15 holes. The tantalum-rich oxide phases wodginite, manganotantalite and microlite were identified during this work.

PEGMATITE TYPES

The Lilypad Lakes pegmatite group, with minimum dimensions of 2 by 6 km (*see* Figure 11.2), is open along strike to the east and west. Host rocks include mafic and felsic to intermediate metavolcanic rocks and clastic metasedimentary rocks, to a lesser extent (Wallace 1978). An array of pegmatite types and sub-types were identified in the pegmatite cluster in reference to the classification of Černý (1989)

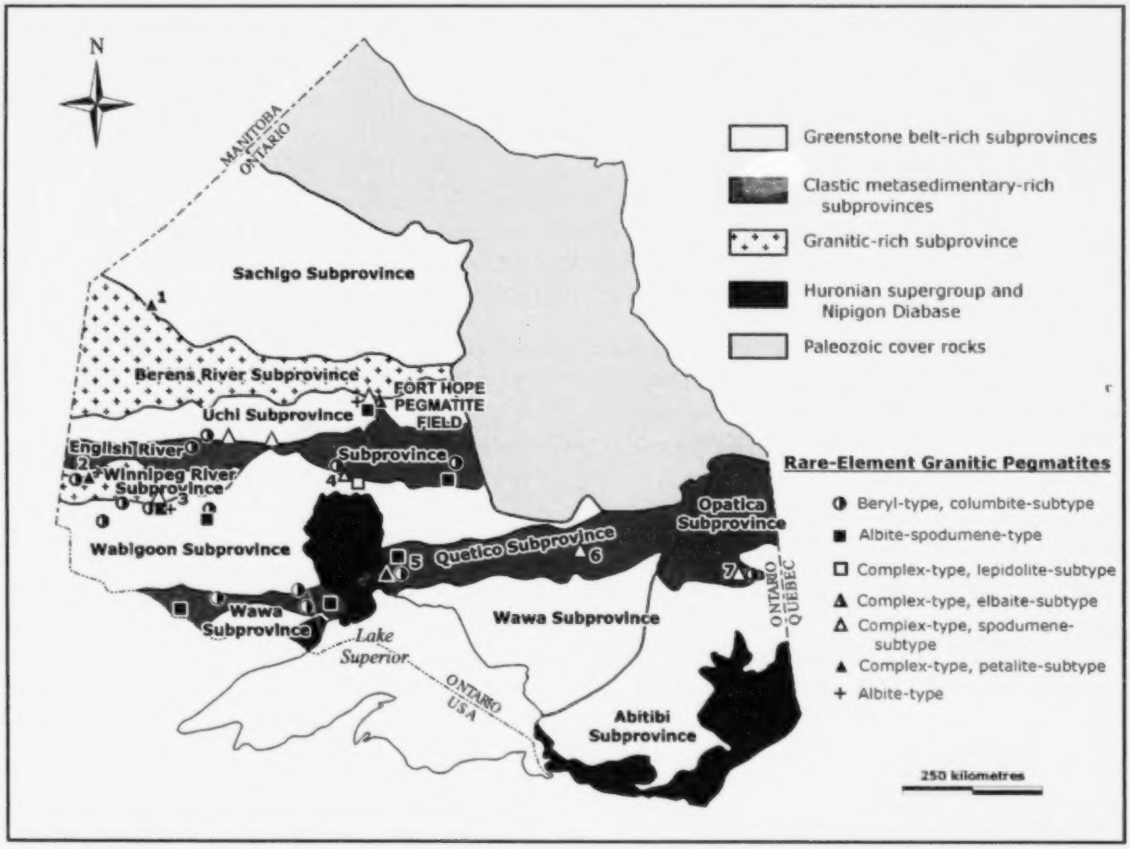
N
MANITOBA
ONTARIO
Greenstone belt-rich subprovinces
Clastic metasedimentary-rich subprovinces
Granitic-rich subprovince
Huronian supergroup and Nipigon Diabase
Paleozoic cover rocks
Sachigo Subprovince
1
Berens River Subprovince
FORT HOPE PEGMATITE FIELD
Uchi Subprovince
English River
2
Winnipeg River Subprovince
3
Subprovince
4
Wabigoon Subprovince
Opatica Subprovince
Quetico Subprovince
5
6
7
Wawa Subprovince
Lake Superior
ONTARIO
USA
ONTARIO
QUEBEC
Abitibi Subprovince
Rare-Element Granitic Pegmatites
Beryl-type, columbite-subtype
Albite-spodumene-type
Complex-type, lepidolite-subtype
Complex-type, elbaite-subtype
Complex-type, spodumene-subtype
Complex-type, petalite-subtype
Albite-type
250 kilometres

Figure 11.1. Location of the Fort Hope pegmatite field in relation other rare-element granitic pegmatites in the Superior Province of Ontario. 1. Pakeagama Lake pegmatite group; 2. Separation Rapids pegmatite group; 3. Dryden pegmatite field; 4. Armstrong pegmatite field; 5. Georgia Lake pegmatite field; 6. Lowther pegmatite; and 7. Case pegmatite.

that belong to the rare-element class, LCT-geochemical family (lithium-cesium-tantalum: Černý 1991).

- Albite-spodumene type
- Complex-type, spodumene-subtype
- Complex-type, elbaite-subtype
- Albite-type

Albite-spodumene-type pegmatites were only observed on former claim PA 27168 (located on Map 2379, Wallace 1977). Deformed dikes, concordant to the foliation in the host rocks, occur over a minimum strike length of 220 m and comprise crudely zoned pegmatites composed of muscovite-green spodumene-potassium feldspar-quartz-albite pegmatite and sodic aplite assemblages (muscovite-quartz-albite). The various pegmatite occurrences over this strike length may be a series of boudins with a maximum individual size of 8 by 40 m at Locality 04-FWB-12 (UTM: NAD83, Zone 15, 5721158E 411833N). Internal parts of the boudins are relatively undeformed as most of the ductile strain was concentrated along the pegmatite–mafic metavolcanic contacts. Accessory minerals include red-brown

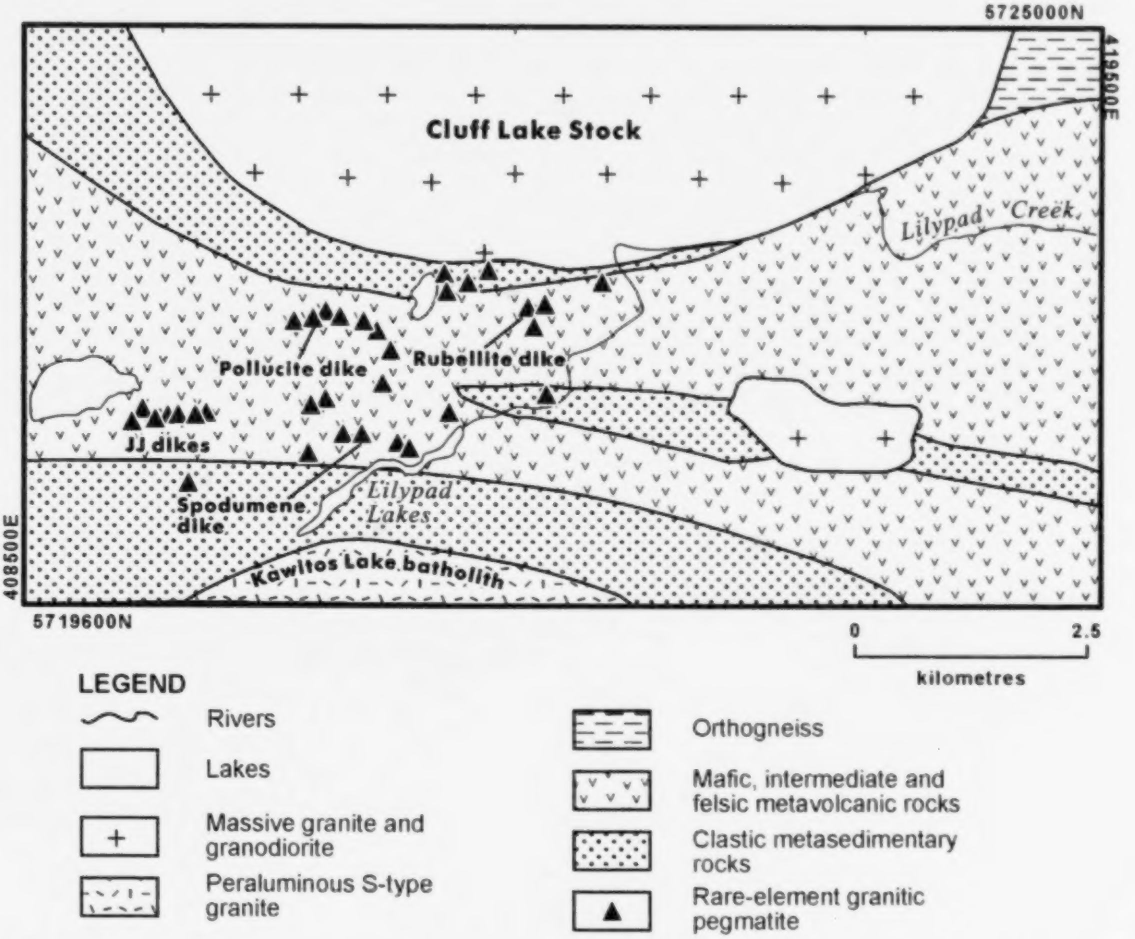
5725000N
419500E
Cluff Lake Stock
Lilypad Creek
Pollucite dike
Rubellite dike
JJ dikes
Spodumene dike
Lilypad Lakes
Kawitos Lake batholith
408500E
5719600N
0
2.5
kilometres
LEGEND
Rivers
Lakes
Massive granite and granodiorite
Peraluminous S-type granite
Orthogneiss
Mafic, intermediate and felsic metavolcanic rocks
Clastic metasedimentary rocks
Rare-element granitic pegmatite

Figure 11.2. Rare-element pegmatite occurrences of the Lilypad Lakes pegmatite group in relation to general geology (*modified after* Wallace 1977, 1978, 1981; Avalon Ventures Limited 2001; Hall, this volume).

garnet, blue apatite, black tourmaline and specks of black oxide minerals. The oxide minerals mainly occur in primary aplite pods that grade into the spodumene pegmatite unit without any evidence of replacement. Alteration of spodumene into soft, dark green to black masses of aphanitic secondary minerals is common, particularly in the western part of the pegmatite swarm. Black tourmaline is sparse and largely concentrated within biotite-rich, metasomatic reaction rims developed along contacts with the mafic metavolcanic host-rock contacts. Conspicuous blue holmquistite locally exhibits a strong linear orientation within a crenulated foliation up to 5 cm from the dike contact. Bulk rock chemical data by Avalon Ventures Limited (2001) on the Spodumene dike (*see* Figure 11.2) revealed low levels of Ta_2O_5 (0.01 weight %), Cs_2O (0.01 weight %) and Rb_2O (0.10 weight %) that reflect the relatively primitive geochemical signature of the albite-spodumene pegmatite type (Černý 1989).

Complex-type, spodumene-type pegmatites are restricted to the Pollucite and Rubellite dikes (*see* Figure 11.2). The Pollucite dike is a deformed, "medium-grained" (Cameron et al. 1949, p.16: 2.5 to 10 cm grain size range) pegmatite that has been traced for 370 m in outcrop and in 8 diamond-drill holes (Avalon Ventures Limited, 2001, p. 28-29). Spodumene is the most pervasive lithium mineral although lepidolite-rich zones occur at the northeast and southwest ends of the 2.5 to 10 by 30 m main outcrop exposure. White, grey and rarely light pink primary spodumene blades are mostly randomly oriented except along the southeast margins of the dike. The margins are, marked by a sub-perpendicular alignment of spodumene crystals relative to internal layers of sodic aplite and to the contact with felsic to intermediate metavolcanic rocks. Bright purple lepidolite occurs as books up to 3 mm thickness and appears as a primary mineral that coexists with albite, quartz, local rubellite, sparse spodumene, possible amblygonite and black to dark brown niobium-tantalum oxide minerals. Pollucite is inconspicuous as recessively weathered, faint brown, interconnected, anhedral masses situated between spodumene, quartz and albite. Exomorphic black tourmaline, biotite and sericite are obvious as 1 to 3 cm thick metasomatic selvages along the pegmatite contacts with intermediate metavolcanic rocks and within enclaves of the same rock type.

The Rubellite dike is exposed in 2 main outcrops, situated along the north and south edges of a prominent linear, east-oriented, topographic depression. These outcrops consist of complex-type, spodumene- and elbaite-subtypes, that correspond to the north and south outcrops, respectively. The latter represents just the second elbaite-subtype pegmatite known in Canada. The first Canadian elbaite-subtype pegmatite is situated in the O'Grady batholith, Northwest Territories (Ercit, Groat and Gault 2003). The spodumene-subtype, north outcrop mainly consists of a rubellite-primary potassium feldspar-quartz-spodumene-albite assemblage with sporadic, white to faint orange amblygonite.

Secondary phases at the north exposure include orange, rubidium-rich microcline with up to 13.44 weight % Rb_2O and rubidian-adularia (up to 22.00 weight % Rb_2O: Teertstra, Černý and Hawthorne 1998, p.486), yellow green to light brown muscovite and bright purple lepidolite that has locally replaced rubellite, pollucite and amyblygonite. Purple fluorite and radiating clusters of tan coloured bavenite occur along late, intersecting fractures. Bavenite $[Ca_4Be_2Al_2Si_9O_{26}(OH)_2]$ may occur as a late hydrothermal primary mineral in miarolitic cavities (Wirth and Green 2003), along joint surfaces, or as an alteration of beryl (Korbel and Novák 1999) and occurs in both outcrop exposures. Tourmaline-rich metasomatic selvages, up to 1 cm thick, occur along the contact with mafic metavolcanic rocks and reveal a black to deep blue colour zonation similar to those of the JJ pegmatite dikes (*see* Figure 11.2), as described below.

The southern outcrop reveals brilliant, pink rubellite as the dominant lithium mineral (10 to 20 modal %), accompanied by minor spodumene (1 to 2 modal %) and lepidolite (3 to 5 modal %), thus supporting the classification of this locality as elbaite-subtype (Novák and Povondra 1995). This part of the Rubellite dike is essentially a pollucite-lepidolite-rubellite-quartz-albite assemblage. Local irregular masses of faint orange, pollucite, up to 17 by 35 cm, are overprinted by albite-rich alteration veinlets that contain local, fine-grained lepidolite. Lepidolite also replaces parts of rubellite prisms and amblygonite masses.

Based upon the Rb_2O contents of primary, blocky potassium feldspar, the Rubellite dike is amongst the most fractionated rare-element pegmatites known in Ontario. Teertstra, Černý and Hawthorne (1998) reported a mean content of 3.44 weight % Rb_2O (range 2.8–4.9 weight %) as compared to other pollucite-bearing pegmatites (Breaks, Selway and Tindle 2004) such as the Tot Lake pegmatite (mean 2.77 weight %; range 1.8–4.3 weight %) and the Pakeagama Lake pegmatite (mean 1.22 weight %; range 1.07–1.32 weight %). The range of Rb_2O from the Rubellite dike overlaps with that of Pegmatite #7 (1.78–5 weight %), a petalite-subtype pegmatite in the Separation Rapids group (Breaks and Tindle 2002).

Albite-type pegmatites were mostly documented in the JJ pegmatites named by Avalon Ventures Limited (*see* Figure 11.2) that occur intermittently along a strike length of 750 m. These narrow, 8 to 40 cm wide, quartz-albite dikes also contain locally miarolitic cavity-bearing, tourmaline group minerals, pollucite and scant yellow-green muscovite, faint blue beryl, potassium feldspar and inconspicuous amblygonite and columbite-tantalite group minerals. The tourmaline group minerals may occur across the dike's breadth and exhibit a colour zonation of black to dark and faint blue within a 1 to 3 cm thick outer rim to faint pink rubellite to colourless achroite varieties (Korbel and Novák 1999) in the dike centre. Avalon Ventures Limited (2001) documented 0.106 weight % Ta_2O_5, 0.48 weight % Rb_2O, 0.61 weight % Li_2O and 0.06 weight % Cs_2O over a 0.45 m width from diamond-drill hole LJJ01-31. To the writers' knowledge, these are the first albite-type pegmatites known globally to contain lithium tourmaline species and pollucite.

Černý (1989) describes albite-type pegmatites as the scarcest of the various types and subtypes on a global scale. These have generally highly evolved Nb/Ta ratios (1.2–0.8: Černý 1989, p.197) and economically interesting Ta contents, but rarely are feasible for mining due to the inherently narrow widths (typically less than 5 m: Černý 1989). An exception is the Wodgina main-lode pegmatite in Western Australia, the largest known example of an albite-type pegmatite that produced tantalum concentrates between 1988 and 1994, from a deposit of 402 000 tonnes grading 0.128 weight % Ta_2O and 0.021 weight % Nb_2O_5 (Fetherston 2004).

POTENTIAL FERTILE GRANITE PLUTONS

A large complex of orthogneiss-peraluminous, S-type granite-*lit-par-lit* paragneiss, named the Kawitos Lake batholith (Wallace 1981, p.60-61), lies a minimum 0.4 km south of the Lilypad Lakes pegmatite group. White, S-type, peraluminous, pegmatitic granite units are generally concordant to layering within the paragneiss (Wallace 1978, 1981). Entrained enclaves of metawacke and banded iron formation are also common (Wallace 1978). A conspicuous 3 by 35 km aeromagnetic pattern, with a range of 191 to 454 nT (Ontario Geological Survey 2003), corresponds to banded iron formation-bearing paragneiss unit that suggests the presence of thrust-stacked, nappe structures (G.M. Stott, personal communication, 2004). The full extent of this granitoid-paragneiss complex is unknown as the region south of Rich Lake has not been mapped in detail. An estimated size for the complex of 35 by 50 km (Breaks 1991, p.244-245) was based upon geophysical aeromagnetic features and existing geological data (Thurston and Carter 1970; Wallace 1978, 1981).

The batholith comprises rock types (Wallace 1978, 1981; Hall, this volume) and elevated rubidium, cesium, lithium and gallium (Černý and Meintzer 1988, p.186) that are characteristic of fertile, S-type, peraluminous granite masses elsewhere along the English River–Uchi subprovince boundary zone (e.g., Allison Lake batholith: Breaks, Selway and Tindle 2003b). Wallace (1978, p.31) identified muscovite pegmatite units (up to 35 modal % muscovite) with lesser black and purple tourmaline (possible schorl-foitite) and fluorite within the Rich Lake area. South of the Fort Hope gold mine, several units were observed by the present survey:

- Garnet-biotite-muscovite grey granite, medium- to coarse-grained, massive
- Tourmaline-muscovite pegmatitic leucogranite, gradational into grey granite
- Apatite-tourmaline-muscovite potassic pegmatite veins that cross-cut the above units

LAKE SEDIMENT GEOCHEMISTRY

A regional survey of lake sediment geochemistry included the Lilypad Lakes pegmatite group and adjacent Kawitos Lake batholith (Ontario Geological Survey 2001; Dyer and Russell 2001). Significant clusters of anomalous cesium, lithium and rubidium in lake sediments occur adjacent to the rare-element pegmatites in the Lilypad Creek drainage basin and over the Kawitos Lake batholith, drained by Rich Creek and tributaries. The cesium anomalies (Figure 11.3), defined by the >98 percentile that corresponds to a range of 1.86 to 13.89 ppm Cs, occur within a 2.5 by 5 km cluster over the Lilypad Lakes pegmatite group and in a 4 by 12.5 km cluster over the Kawitos Lake batholith. The latter anomalous area, associated with a drainage basin unconnected with Lilypad Creek, is intriguing and implies pollucite mineralization associated with highly fractionated pegmatitic granites in this batholith.

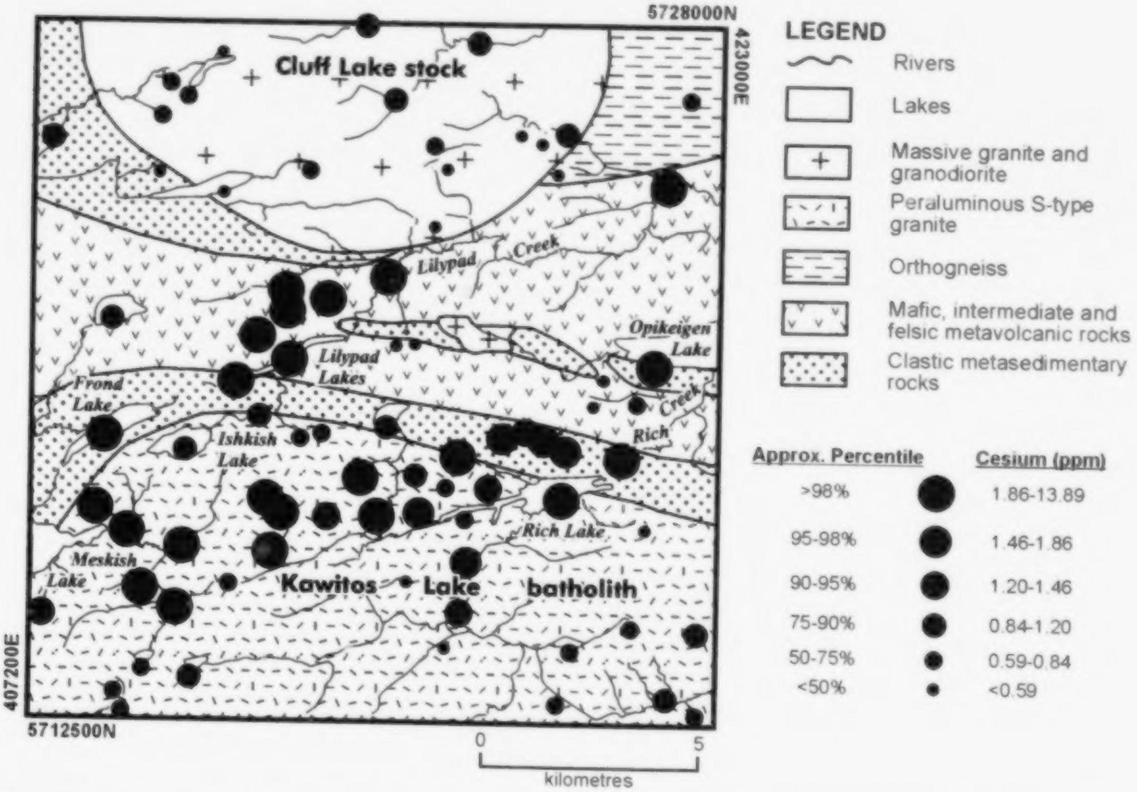
5728000N
423000E
Cluff Lake stock
Lilypad Creek
Opikeigen Lake
Lilypad Lakes
Frond Lake
Ishkish Lake
Rich Creek
Rich Lake
Meskish Lake
Kawitos Lake batholith
407200E
5712500N
0
5
kilometres
LEGEND
Rivers
Lakes
Massive granite and granodiorite
Peraluminous S-type granite
Orthogneiss
Mafic, intermediate and felsic metavolcanic rocks
Clastic metasedimentary rocks
Approx. Percentile
Cesium (ppm)
>98% 1.86-13.89
95-98% 1.46-1.86
90-95% 1.20-1.46
75-90% 0.84-1.20
50-75% 0.59-0.84
<50% <0.59

Figure 11.3. Cesium in lake sediment samples, Fort Hope lake sediment survey, Lilypad Lakes area (*modified after* Dyer and Russell 2001).

The cesium lake sediment anomalies are explicable by the schematic sequence proposed by Teertstra and Černý (1995, p.1147) that depicts the relative timing of alteration processes of the pollucite-analcime series. These workers documented a late stage of hydrothermal breakdown of the pollucite and progressive replacement by analcime + fluid dispersion at 150 to 200°C via hydrothermal solutions probably guided by fractures. This process is followed by the development of pseudomorphs composed of clay minerals (illite, kaolinite and expanding-type smectites) after pollucite due to hydrothermal alteration below 100°C (Teertstra and Černý 1995). Černý (1978) documented that clay-rich nodules with 0.05 to 0.24 weight % Cs_2O were formed from altered pollucite in several Manitoba pegmatites. The final stage involves the dissolution of pollucite due to weathering. Černý (1978) noted that pollucite at the Tin Mountain pegmatite in South Dakota was transformed into montmorillonite after 6 months of being freshly exposed to surficial weathering.

Pollucite at the 4 other Ontario localities (Breaks, Selway and Tindle 2004) typically occurs as recessive areas on weathered surfaces, relative to more resistant, coexisting phases such as quartz, albite, spodumene and potassium feldspar. This phenomenon was also observed at the Rubellite, Pollucite and JJ dikes. Final dissolution of the mineral plausibly occurred during weathering due to interaction with humic acids of low pH derived from organic material in the overlying soils. The leaching power of humic acids is demonstrated by the characteristic ashen, A-horizon of podzolic soils (Buckman and Brady 1960) that occur in well-drained sand and gravel parent materials of soils in the area. Transfer of Cs^+ and Rb^+ cations from clay minerals that replaced pollucite, via exchange with Ca^{2+}, K^+ and Na^+ in soil fluids, and thence into drainage systems is a possible explanation for anomalous cesium and rubidium contents in lake sediments, proximal to the Rubellite and Pollucite dikes (*see* Figure 11.3). Rubidium is a minor element in secondary pollucite at the Rubellite dike with a mean content of 0.60 weight % Rb_2O (Teertstra and Černý 1995, p.1145) and weathering release of such rubidium could explain rubidium lake sediment anomalies in the area. Weathering similarly affects amblygonite that has been observed as recessive weathered mineral on the surface of the Rubellite dike and also at the Pakeagama Lake pegmatite (Breaks, Tindle and Smith 1998). Lithium released via weathering of amblygonite [$LiAlPO_4(F,OH)$] could explain the presence of lithium anomalies in nearby lake sediment samples (Dyer and Russell 2001), as other lithium phases, such as lepidolite, elbaite and spodumene are highly resistant to weathering.

EXPLORATION RECOMMENDATIONS

The Fort Hope pegmatite field contains some of the most evolved rare-element granitic pegmatites in Ontario. This is substantiated by the widespread presence of the pollucite-analcime series, a mineralogical indicator of extreme chemical fractionation (Černý, Meintzer and Anderson 1985), coupled with primary blocky potassium feldspar compositions whose Rb_2O contents mostly exceeds other pollucite-bearing pegmatites in Ontario (Breaks, Selway and Tindle 2004).

Further exploration for rare-element granitic pegmatites is accordingly merited in the area, particularly in poorly exposed parts of the Lilypad Lakes pegmatite group to the east from the highly evolved Rubellite dike and west of the albite-type pegmatites of the JJ dikes. Here, exploration tools such as the Enzyme Leach^{SM} technique (Galeschuk and Vanstone 2004), boulder tracing and stream sediment sampling may be useful.

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12. Project Unit 95-014. Geology of the Lac des Mille Lacs Area

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INTRODUCTION

The Lac des Mille Lacs area is situated approximately 100 km west of Thunder Bay, Ontario. The area can be reached by Trans Canada Highway 17 and a network of logging roads joined to highways 17 and 11. Water bodies including Lac des Mille Lacs and the Seine River system provide further access to the area.

Previous geologic mapping in the Lac des Mille Lacs area includes the work of Irvine (1963) and Kaye (1967). The area is underlain by metamorphosed Archean sedimentary volcanic and plutonic sequences, all of which are extensively blanketed by thick Quaternary till, glacial ice-margin and glaciofluvial deposits. From south to north, the bedrock is represented by wacke-siltstone sequences of the Quetico Subprovince, the Lac des Mille Lacs greenstone belt and extensive tonalitic to granitic batholiths. The Lac des Mille Lacs area is situated at the south margin of the Marmion terrane in the central Wabigoon Subprovince (Figure 12.1).

The present work is a continuation of geologic mapping in the central Wabigoon Subprovince by the Ontario Geological Survey. Goals of the mapping are to define the regional geology including major crustal blocks of divergent Mesoarchean and Neoarchean age as well as to provide new targets for mineral exploration. Details of the geology, tectonic evolution and mineral potential of the Lac des Mille Lacs area are discussed further below.

GEOLOGY

Quetico Sedimentary Sequences

Variably metamorphosed sedimentary rocks occur in the south part of the Lac des Mille Lacs area (Figures 12.2 and 12.3). These sedimentary sequences of the Quetico Subprovince are traced eastward through Minnesota and Ontario for a distance of more than 1000 km (*see* Figure 12.1). Extensive geochronologic work on detrital zircon grains showed that the Quetico Subprovince sedimentary sequences were deposited after 2698 Ma in the Atikokan–Rainy Lake area (Davis, Pezzutto and Ojakangas 1990). At many localities, including the present area, the sedimentary rocks are in fault contact with volcanic sequences to the north and are intruded by a variety of felsic plutons.

Sedimentary rocks of the Quetico Subprovince include mainly thin- to thick-bedded wacke and siltstone. Iron formation is interpreted on the basis of aeromagnetic maps (e.g., OGS 1980a, 1980b) to occur at scattered localities typically near the north margin of the sedimentary belt such as at Bolton Bay and Peterkin Lake (*see* Figure 12.3). Conglomerate is observed along the log road 5 km east of Bolton Bay and also at Dexter Lake.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.12-1 to 12-11.

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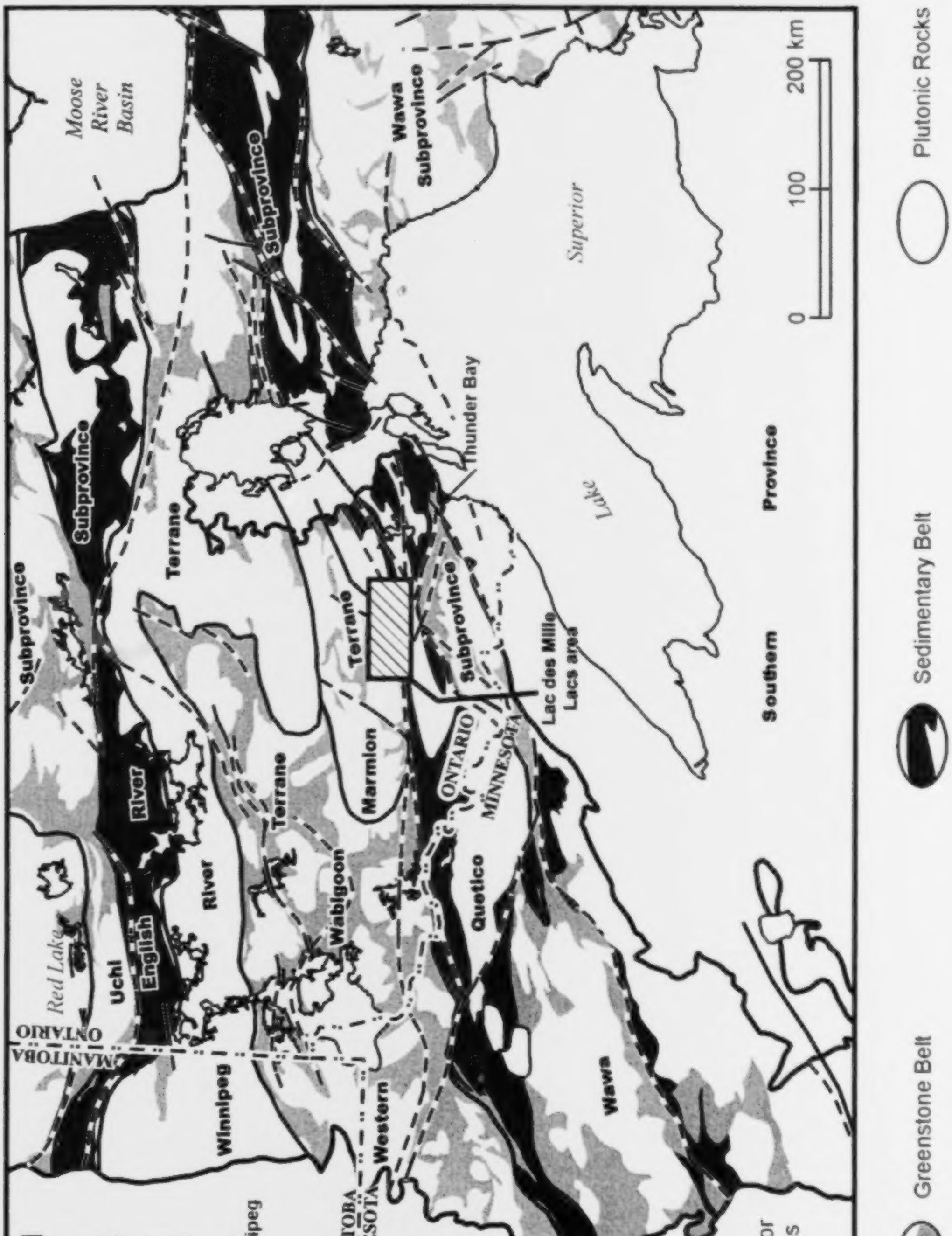
N
Winnipeg
Interior Plains
MANITOBA
MINNESOTA
MANITOBA
ONTARIO
Red Lake
Uchi
English
River
Subprovince
Winnipeg
River
Terrane
Western
Wabigoon
Terrane
Marmion
Terrane
Subprovince
Terrane
ONTARIO
MINNESOTA
Quetico
Subprovince
Lac des Mille Lacs area
Thunder Bay
Subprovince
Wawa
Subprovince
Wawa
Moose River Basin
Lake Superior
Southern Province
0
100
200 km
Greenstone Belt
Sedimentary Belt
Plutonic Rocks

Figure 12.1. Subprovinces and terranes of the southern part of the northwest Superior Province (*modified after* Tomlinson et al. 2004).

Sedimentary beds are subvertical and are composed of massive sand, thinly laminated silt and gradations from sand- to silt-sized particles. Graded beds provide an indication of the stratigraphic top of the sedimentary sequence where deformation is low such as along the north boundary of the Quetico Subprovince. The top of the sequence is invariably north at these localities.

At the north boundary of the Quetico Subprovince, wacke has a mineral assemblage of feldspar + quartz + chlorite. Metamorphic grade increases southward with the appearance of biotite, biotite + amphibole and biotite + amphibole + garnet assemblages. Staurolite is observed locally. At a distance of a few kilometres south of the north boundary, the sedimentary rocks have been partially melted and migmatites characterized by alternating bands of dark wacke paleosome and white granite neosome are developed.

LAC DES MILLE LACS GREENSTONE BELT

The Lac des Mille Lacs greenstone belt extends eastward through the area attaining a width of up to 5 km (*see* Figures 12.2 and 12.3). It is part of a continuous chain of greenstone belts along the south margin of the Wabigoon Subprovince including the Steep Rock Lake greenstone belt to the west (Stone, Kamineni and Jackson 1992) and volcanic rocks at Legris Lake to the east (Hart, MacDonald and Lepine 2001).

The Lac des Mille Lacs greenstone belt is composed of extrusive and intrusive mafic igneous rocks intermediate to felsic dominantly fragmental volcanic rocks and rare sedimentary units. In the area of Chief Peter Lake (*see* Figure 12.2), conglomerate occurs at the north contact of the Lac des Mille Lacs greenstone belt adjacent to tonalite of the Marmion batholith. The conglomerate attains a width of up to a few hundred metres, and contains a variety of deformed mafic, intermediate and felsic clasts possibly representative of gabbro, mafic tonalite and felsic volcanic protoliths, respectively. Thick graded beds demonstrate that the conglomerate youngs south and is overlain by intermediate volcanic breccias and flows.

The intermediate volcanic rocks are cut by anastomosed gabbro dikes that coalesce as an extensive unit of gabbro within the western part of the belt. Rare pillowed mafic flows, fragments of the intruded intermediate volcanic sequences and iron formation occur within the gabbro. The gabbro is characteristically medium to coarse grained and black and is composed of hornblende + plagioclase. Although not strongly foliated, the gabbro tends to be highly fractured, veined and cut by mesoscopic faults.

Mafic volcanic flows occur south of the gabbro and extend discontinuously along the south margin of the Lac des Mille Lacs greenstone belt. The mafic flows are distinguished from the massive mafic units to the north by mainly pillowed sequences showing a mineral assemblage of plagioclase + actinolite + epidote ± chlorite. The pillowed mafic sequence is weakly deformed at most localities and youngs southward becoming schistose where sheared by the Quetico fault at the south margin of the greenstone belt.

At Lac des Mille Lacs, the north margin of the Lac des Mille Lacs greenstone belt is intruded by foliated hornblende tonalite and a younger elongate biotite granite pluton. At this locality, on the greenstone belt margin, conglomerate is not observed and intermediate volcanic flows tuffs and breccias predominate. The volcanic rocks are typically fine grained, grey, hard and have a mineral assemblage of quartz + feldspar + biotite. The intermediate volcanic fragmental sequence is represented by a U/Pb zircon age of 2830.2±1.1 Ma (Tomlinson et al. 2003) and is cut by gabbro dikes and late discordant dikes of peridotite. Southward, the intermediate volcanic sequence is in contact with south-younging pillowed mafic volcanic rocks associated with units of felsic tuff and gabbro. The mafic sequence has a mineral assemblage of plagioclase + actinolite + epidote ± chlorite.

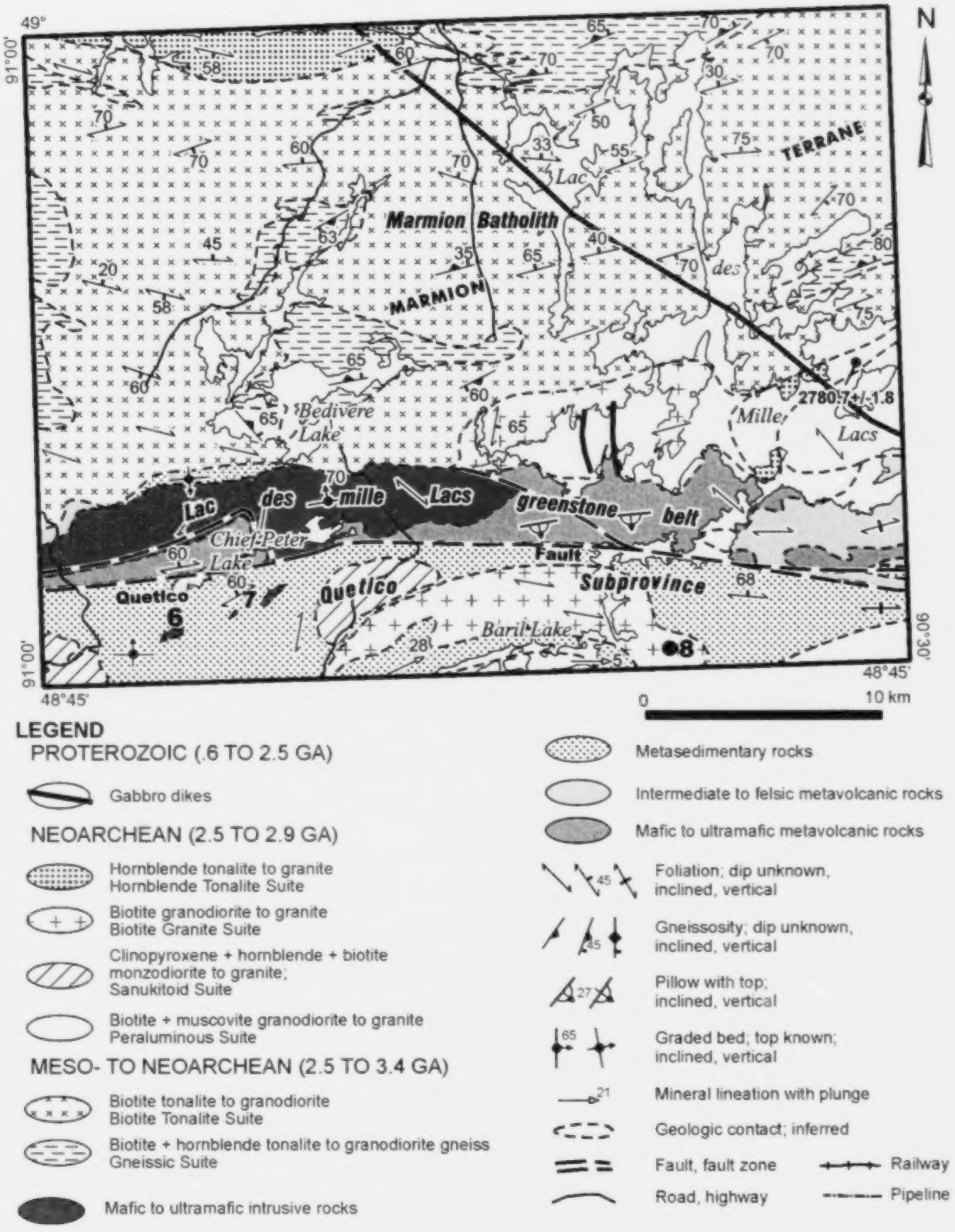
49°
91°00'
N
TERRANE
Marmion Batholith
MARMION
Lac
des
Mille
Lacs
2780.7+/-1.8
Bedivere Lake
Lac des mille Lacs greenstone belt
Chief Peter Lake
Fault
Quetico
6
7
Quetico Subprovince
Baril Lake
8
91°00'
48°45'
90°30'
48°45'
0
10 km
LEGEND
PROTEROZOIC (.6 TO 2.5 GA)
Gabbro dikes
NEOARCHEAN (2.5 TO 2.9 GA)
Hornblende tonalite to granite
Hornblende Tonalite Suite
Biotite granodiorite to granite
Biotite Granite Suite
Clinopyroxene + hornblende + biotite monzodiorite to granite;
Sanukitoid Suite
Biotite + muscovite granodiorite to granite
Peraluminous Suite
MESO- TO NEOARCHEAN (2.5 TO 3.4 GA)
Biotite tonalite to granodiorite
Biotite Tonalite Suite
Biotite + hornblende tonalite to granodiorite gneiss
Gneissic Suite
Mafic to ultramafic intrusive rocks
Metasedimentary rocks
Intermediate to felsic metavolcanic rocks
Mafic to ultramafic metavolcanic rocks
Foliation; dip unknown, inclined, vertical
Gneissosity; dip unknown, inclined, vertical
Pillow with top; inclined, vertical
Graded bed; top known; inclined, vertical
Mineral lineation with plunge
Geologic contact; inferred
Fault, fault zone
Railway
Road, highway
Pipeline

Figure 12.2. Geology of the western Lac des Mille Lacs area.

The Lac des Mille Lacs greenstone belt tapers east of Lac des Mille Lacs and is poorly exposed and possibly discontinuous in the vicinity of Highway 17 (*see* Figure 12.3). Outcrops of intermediate volcanic rocks, gabbro and gneissic amphibolite are observed north of Peterkin Lake. The greenstone belt is cut by the Shelby Lake fault east of Lac des Mille Lacs and most exposed rocks are strongly foliated. The metamorphic grade is amphibolite facies with the gneissic amphibolite possibly representing deformed and metamorphosed extensions of the pillowed mafic sequences to the west.

PLUTONIC ROCKS

The Lac des Mille Lacs area is represented by six major suites of igneous rocks ranging compositionally from tonalite and granite to gabbro and peridotite. The biotite tonalite and tonalite gneiss suites occur extensively in the Marmion batholith in the northwest part of the area (*see* Figures 12.2 and 12.3). The grey, foliated tonalitic rocks of the Marmion batholith extend west to the Atikokan area where geochronologic studies have yielded ages close to 3000 Ma (Tomlinson et al. 2003). Units of biotite tonalite and tonalite gneiss also occur in the Quetico Subprovince at Raith. Although an unconformity is not observed, sedimentary sequences adjacent to the tonalite units contain conglomerate beds and imply that the tonalite can represent a rare example of a preserved basement complex within the Quetico Subprovince.

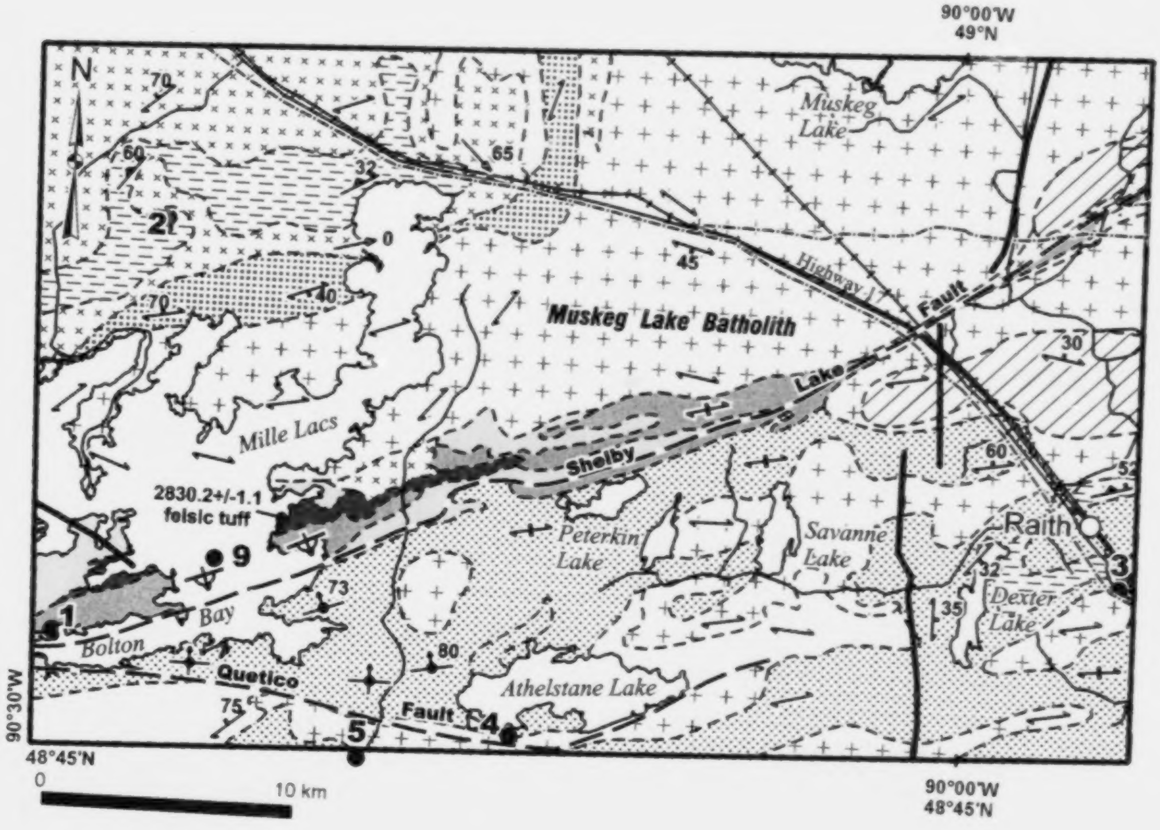
90°00'W
49°N
N
70
60
32
65
2
0
45
40
70
Muskeg Lake
Highway 17
Fault
Muskeg Lake Batholith
Lake
Shelby
Mille Lacs
30
60
52
2830.2+/-1.1
felsic tuff
9
Peterkin Lake
Savanne Lake
Raith
3
32
35
Dexter Lake
1
Bolton
Bay
73
80
Quetico
Athelstane Lake
75
Fault
5
4
90°30'W
48°45'N
0
10 km
90°00'W
48°45'N

Figure 12.3. Geology of the eastern Lac des Mille Lacs area. For legend, see Figure 12.2.

Foliated hornblende tonalite of the hornblende tonalite suite occurs as small, scattered units and in an elongate belt mantling the eastern end of the Marmion batholith at Lac des Mille Lacs. The belt-like unit of hornblende tonalite also intrudes the Lac des Mille Lacs greenstone belt and has an age of 2780.7±1.8 Ma (Tomlinson et al. 2003).

Biotite granodiorite to granite of the biotite granite suite occurs widely in forms ranging from dikes to large batholiths. A foliated biotite granodiorite pluton has intruded the north side of the Lac des Mille Lacs greenstone belt at Lac des Mille Lacs. This pluton grades into a massive potassium-feldspar megacrystic granite batholith to the northeast. Various oval to elongate plutons of the biotite granite suite intrude Quetico Subprovince sedimentary sequences. The massive megacrystic phases may be correlative in age with the 2685 million-years-old White Otter batholith north of Atikokan (Davis 1993).

Peraluminous or two-mica granite occurs extensively within the Quetico Subprovince and appears to have been derived by partial melting of the sedimentary rocks. Peraluminous granite is coarse grained, white and may contain biotite and muscovite as well as accessory garnet, tourmaline and apatite. Peraluminous granite occurs on a local scale as *lit-par-lit* bands within sedimentary migmatites and on a regional scale as oval plutons intruding the Quetico Subprovince sedimentary sequences.

Oval intrusions that range in composition from hornblendite through diorite to monzodiorite and syenite and belonging to the sanukitoid suite occur in the Quetico Subprovince. These include the Elbow Lake intrusion, part of which occurs in the southwest corner of the area (*see* Figure 12.2) and the Miserable Lake intrusion located 5 km southeast of Chief Peter Lake. The Elbow Lake intrusion is composed of hornblendite, diorite and monzodiorite. The Miserable Lake intrusion has a thin, discontinuous rim of hornblendite and a core of syenite. Monzodioritic to granodioritic intrusions of the sanukitoid suite occur north of Raith at the east side of the area. Small syenitic stocks are mapped in the Athelstane Lake area (localities 4 and 5 of Figure 12.3).

Sanukitoid plutons were emplaced late in the tectonic evolution of the area and show a spatial association with major faults. Sanukitoid plutons located west of the area at Sapawe and northeast of the area at Shelby Lake have ages of 2688 and 2690 Ma, respectively (Davis, Pezzutto and Ojakangas 1990; S.L. Kamo, Jack Satterly Geochronology Laboratory, personal communications, 2004).

Several varieties of mafic to ultramafic intrusions occur in the area. Among these are extensive dikes, sills and masses of hornblende gabbro within the Lac des Mille Lacs greenstone belt such as north of Chief Peter Lake. These massive to foliated intrusions postdate felsic volcanic sequences, which have an age of 2830 Ma, however, the highly deformed and metamorphosed character of the intrusions implies that the intrusions were emplaced at an early stage of greenstone belt development.

In contrast to the deformed gabbro bodies, several late, weakly deformed and metamorphosed mafic to ultramafic intrusions occur at scattered localities. Stocks and dikes of gabbro, hornblendite and peridotite intrude Quetico Subprovince sedimentary sequences 5 km southwest of Chief Peter Lake (*see* localities 6 and 7 of Figure 12.2). These intrusions, locally known as the Chief Peter Lake intrusions (K. Fenwick, Historical Prospecting, personal communications, 2004), have been explored sporadically for copper, nickel and platinum group elements (Irvine 1963). Recent mapping by Intrepid Minerals Corporation (Assessment File 2.23460, Thunder Bay Resident Geologist's Office) shows that the western intrusion has a peridotitic core rimmed by hornblendite. The dike-like eastern intrusion (locality 7) is composed of hornblendite and several smaller intrusive bodies of gabbro are noted locally.

The present mapping has identified other late mafic intrusive bodies possibly correlative with the Chief Peter Lake intrusions. An oval stock (approximately 800 m diameter) of coarse-grained varitextured gabbro and hornblendite intrudes gneisses of the Marmion batholith north of central Lac des

Mille Lacs (*see* locality 2 of Figure 12.3). Discordant dikes of peridotitic to pyroxenitic composition cut volcanic sequences of the Lac des Mille Lacs greenstone belt. The dikes strike northerly and northeasterly and attain a width of up to 100 m where exposed on islands in Lac des Mille Lacs north of Bolton Bay (represented by locality 9 in Figure 12.3). The dikes have a strong aeromagnetic expression (OGS 1980a, 1980b) and are interpreted to extend up to 2 km northerly and 5 km northeasterly.

Large angular boulders of hornblendite and peridotite occur on the shores of a small crescentic pond 4 km east of Baril Lake (*see* locality 8 of Figure 12.2). Although no bedrock exposures were identified, the large size, angularity and abundance of the boulders suggest that they could have been derived locally from an ultramafic body that is blanketed by Quaternary deposits.

Hornblendite boulders are noted along log roads 5 km southwest of Savanne Lake and along the north-trending road east of Lac des Mille Lacs. The boulders allude to unknown potentially small, dike-like ultramafic bodies in the area. A small hornblendite dike cuts Quetico Subprovince sedimentary sequences in a rock cut adjacent to Highway 17 south of Raith (locality 3 of Figure 12.3). The dike of approximately 1.0 m width is locally foliated and contains anomalous concentrations of platinum group elements (B. Schneiders, Resident Geologist, personal communications, 2004).

The weakly deformed and metamorphosed mafic to ultramafic intrusions of the Lac des Mille Lacs area are correlative with the Quetico suite of mafic to ultramafic intrusions (Pettigrew, Hattori and Percival, 2000). The Quetico suite is represented by a series of late mafic to ultramafic stocks and dikes intruding Quetico Subprovince sedimentary sequences and plutonic rocks of the southern Wabigoon Subprovince. These intrusions are scattered over a distance of 200 km from the Minnesota border in the west to north of Thunder Bay in the east. The Quetico suite appears to represent a continuation of the Lac des Iles suite of mafic to ultramafic bodies located approximately 100 km north of Thunder Bay (Stone et al. 2003). Several intrusions of the Lac des Iles suite including the Tib and Mine Block intrusions have U/Pb zircon ages of 2686 to 2689 Ma (Davis 2003).

Rare sets of north- and northwest-trending diabase dikes of probable Proterozoic age transect the area (*see* Figures 12.2 and 12.3).

FAULTS

Two major faults are identified in the Lac des Mille Lacs area. The Quetico fault is marked by a zone schistose supracrustal rocks developed over a width of a few hundred metres and traced eastward along the south side of the Lac des Mille Lacs greenstone belt (*see* Figures 12.2 and 12.3). At Bolton Bay, the Quetico fault curves slightly southeastward into the Quetico Subprovince and is traced as far as Athelstane Lake (*see* Figure 12.3). The Quetico fault is developed discontinuously along the Quetico–Wabigoon Subprovince boundary and structural evidence indicates mainly dextral transcurrent displacement (Stone, Kamineni and Jackson 1992). At Bolton Bay, Quetico Subprovince sedimentary sequences show a marked increase in metamorphic grade southward across the fault implying a local south-side-up component of displacement.

Previous mapping by Stone et al. (2003) has traced the Shelby Lake fault southwest from the Mine Block intrusion at Lac des Iles into the present area. Although poorly exposed in the present area, the Shelby Lake fault appears to cut the Lac des Mille Lacs greenstone belt east of Lac des Mille Lacs (*see* Figure 12.3) and merges with the Quetico fault at Bolton Bay. No noticeable change in metamorphic grade is observed across the Shelby Lake fault at Bolton Bay.

TECTONIC EVOLUTION OF THE MARMION TERRANE

The Superior Province of northwest Ontario has been historically subdivided into a series of easterly trending volcano-plutonic and sedimentary subprovinces including the Wabigoon and Quetico subprovinces (Card and Ciesielski 1986). With the advent of accretionary tectonic models for the growth of Archean cratons, many authors proposed that the subprovinces represent various crustal elements that were assembled into the Superior Province. For example, the volcanic and sedimentary subprovinces have been interpreted as volcanic arcs and sedimentary prisms respectively that were accreted together from north to south at approximately 2.69 Ga (e.g., Percival and Williams 1989).

Geochronologic investigations (e.g., Davis and Jackson 1988) showed that the Wabigoon Subprovince is composed of rocks varying in age from 3.0 to 2.7 Ga. This wide range of ages is inconsistent with the Wabigoon Subprovince representing a single volcanic arc and has led to new research including the present work. Recent tectonic interpretations based largely on neodymium studies (Tomlinson et al. 2004) have subdivided the former Wabigoon Subprovince into crustal blocks including the Winnipeg River terrane, Marmion terrane and Western Wabigoon terrane (*see* Figure 12.1). These crustal blocks are thought to have developed independently through the late Mesoarchean and Neoarchean and were tectonically amalgamated at approximately 2.71 Ga followed by accretion of the Quetico Subprovince sedimentary sequences along the southern flank at 2.69 Ga.

The present area is situated on the southern Marmion terrane and adjacent Quetico Subprovince and provides new insight on the tectonic evolution of the Marmion terrane. Tomlinson et al. (2004) defined the Marmion terrane as an old crustal block composed of a three-billion-year-old basement complex and somewhat younger magmatic sequences that show isotopic evidence of having interacted the older basement. The 3.0 Ga Marmion batholith extends 100 km east from Atikokan and represents the basement complex in the south central part of the Marmion terrane. The Lumby Lake and Finlayson Lake greenstone belts on the north and northwest margins of the batholith contain a variety of volcanic assemblages with ages of 3.01, 3.00, 2.96, 2.93 and 2.83 Ga (Tomlinson et al. 2003). Extensive tonalitic areas in the north and northeast parts of the Marmion terrane are represented by an age of 2.92 Ga (S.L. Kamo, Jack Satterly Geochronology Laboratory, personal communications, 2004).

The southwest end of the Marmion batholith is unconformably overlain by the Steep Rock Lake Group, which comprises units of basal conglomerate, carbonate, iron formation and ultramafic lapilli tuff (ashrock). Although the ashrock was erupted after 2.78 Ga, the basal conglomerate contains circa 3.0 Ga detrital zircon grains (Tomlinson et al. 2003) and could be nearly as old as the Marmion batholith. The Steep Rock Lake Group is in fault contact with pillowed mafic volcanic rocks (Witch Bay Formation of Wilks and Nisbet 1988) that occupy most of the southwestern Steep Rock Lake greenstone belt.

The conglomerate northwest of Chief Peter Lake is possibly correlative with the basal conglomerate unit of the Steep Rock Lake Group. In the Chief Peter Lake area, the conglomerate is overlain by felsic volcanic rocks with an interpreted age of 2.83 Ga based on an age determination on similar rocks 40 km east at Lac des Mille Lacs. This suggests that the conglomerates at Chief Peter Lake and also possibly in the Steep Rock Lake Group are older than 2.83 Ga. At Chief Peter Lake, the Marmion batholith and conglomerate and felsic volcanic units are cut by an extensive network of gabbro dikes. These coalesced dikes comprise much of the northern part of the Lac des Mille Lacs greenstone belt as well as the linear western arm of the belt through the Sapawe–Atikokan area. The gabbro dikes provide geologic evidence for crustal extension along a linear zone of 100 km length at the south side of the Marmion batholith and are interpreted to indicate a rifting event after 2.83 Ga. The rifting event is possibly correlative with eruption of the komatiitic ashrock at Steep Rock Lake, which shows geochemical evidence of having originated in a mantle plume (Tomlinson et al. 1999).

The pillowed mafic volcanic rocks occupying much of the southern part of the Lac des Mille Lacs greenstone belt appear to represent a volcanic assemblage distinct from the mafic dikes to the north. The pillowed volcanic rocks are possibly slices of oceanic material, obducted onto the rifted continental margin prior to accretion of the Quetico sedimentary sequences. The pillowed volcanic assemblage at Lac des Mille Lacs occupies a similar structural position outboard of continental margin sequences as does the Witch Bay Formation at Steep Rock Lake. Although Tomlinson et al. (2004) correlated the Witch Bay Formation with 2.93 Ga volcanic sequences at Finlayson Lake on geochemical evidence, the Witch Bay Formation and other mafic units at the extreme south margin of the Wabigoon Subprovince may alternatively represent fairly young and juvenile oceanic material.

The tonalite gneisses and conglomerate within Quetico Subprovince sedimentary rocks at Raith indicate that at least eastern parts of the Quetico sequences could have been deposited on older continental crust. The Raith gneisses occur south of the rifted margin of the Marmion terrane and possibly represent a detached fragment of the Marmion terrane. Alternatively, the Raith gneisses can be an exotic crustal fragment accreted to the Marmion terrane during or prior to deposition of the Quetico Subprovince sedimentary rocks.

RECOMMENDATIONS FOR MINERAL EXPLORATION

The Lac des Mille Lacs area shows potential for a wide variety of mineralization including gold, base metals and platinum group metals. The Quetico and Shelby Lake faults cut greenstone sequences of the area and provide structural conditions suitable for gold mineralization. For example, splays of the Quetico fault envelope a unit of pillowed mafic volcanic rocks at Chief Peter Lake. The rocks affected by this fault are schistose and show chlorite + carbonate alteration with quartz vein development and can be hosts for gold mineralization. The Quetico fault cuts through islands in Baril Bay of Lac des Mille Lacs (north of Baril Lake in Figure 12.2). Pyritic quartz + carbonate veins are noted within sheared volcanic sequences on the islands in Baril Bay.

Volcanic sequences north of Bolton Bay (locality 1 of Figure 12.3) are strongly schistose, crenulated and altered and show local quartz vein development. This deformation, possibly related to the intersection of the Shelby Lake and Quetico faults appears to have created pathways for fluid movement with resulting wall rock alteration and potential for gold mineralization.

East of Lac des Mille Lacs, the Lac des Mille Lacs greenstone belt is composed of alternating units of gabbro and felsic and mafic volcanic rocks cut by the Shelby Lake fault. Variations in competency between these units during deformation could have produced dilatant zones and pathways for hydrothermal fluids. Although poorly exposed, the eastern Lac des Mille Lacs greenstone belt is a potential source of gold mineralization.

The Chief Peter Lake intrusions (localities 6 and 7 of Figure 12.2) have been explored for copper and nickel and recently for platinum group metals. Grab samples of ultramafic material collected by the author from exploration trenches on the eastern intrusion contain up to 20% sulphide minerals including chalcopyrite, and assays of up to 2.95 g/tonne platinum+palladium are reported (K. Fenwick, Historical Prospecting, personal communications, 2004).

The present mapping shows that the Chief Peter Lake intrusions are part of a chain of quartz-undersaturated igneous bodies including the Elbow Lake intrusion (southwest corner of Figure 12.2) and the oval Miserable Lake intrusion (5 km southeast of Chief Peter Lake). Ultramafic material comprising mainly hornblendite occurs in the northern part of the Elbow Lake intrusion and as a discontinuous rim as well as inclusions within the Miserable Lake intrusion. One of the above inclusions contains up to 10%

finely disseminated sulphide minerals. The ultramafic components of the Elbow Lake and Miserable Lake intrusions are lithologically similar to those of the Chief Peter Lake intrusions and need to be evaluated for base metals and platinum-group metals.

Several, new mafic to ultramafic bodies with potential for base metal and platinum group metal mineralization are identified. These include the gabbro stock north of Lac des Mille Lacs (locality 2 of Figure 12.3) and the ultramafic dikes exposed on islands in Lac des Mille Lacs (locality 9 of Figure 12.3). The bedrock source of ultramafic boulders east of Baril Lake (locality 8 of Figure 12.2) provides another potential source of mineralization.

SUMMARY

New mapping has helped to define major lithologic elements and tectonic evolution of the south central Wabigoon Subprovince in northwest Ontario. The 3.0 Ga Marmion tonalite batholith represents a basement complex on which supracrustal and igneous sequences comprising the Marmion terrane developed in the late Mesoarchean and Neoarchean. The Marmion batholith has been traced eastward for 100 km from Atikokan to the Lac des Mille Lacs area where it terminates against younger intrusive granite of the Muskeg Lake batholith. East of Lac des Mille Lacs magmatic rocks may have been isotopically influenced by the old basement complex, however, the Marmion batholith itself does not appear to extend into this area.

The Lac des Mille Lacs greenstone belt comprises at least three supracrustal assemblages whose structural superposition provides insight on tectonic evolution of the Marmion terrane. An early clastic sedimentary platform sequence developed on the Marmion batholith and was succeeded by felsic volcanic rocks, probably erupted at 2.83 Ga. A linear zone of anastomosed gabbro dikes cut the basement and early supracrustal sequences and is interpreted to mark a rift that developed after 2.83 Ga along the south margin of the Marmion terrane. An assemblage of oceanic basalt, represented by pillowed mafic volcanic rocks at the south side of the Lac des Mille Lacs greenstone belt, was tectonically joined to the south margin of the Marmion terrane prior to accretion of Quetico Subprovince sedimentary sequences at 2.69 Ga.

Although Quetico Subprovince sedimentary sequences have been previously interpreted as vestiges of a sedimentary prism developed in an ocean basin adjacent to the Wabigoon volcanic arc, the mapping shows that at least part of the eastern Quetico sequences were probably deposited on tonalitic basement. The tectonic implications of the Quetico Subprovince basement complex are unclear at present and can possibly be resolved by geochronologic research on the Raith gneisses and further mapping east of the present area.

The Lac des Mille Lacs area is cut by late major faults including the Quetico and Shelby Lake faults. Deformation caused by these faults and associated secondary faults has produced conduits for fluid migration with alteration zones, quartz veins and potential for gold mineralization at several localities in the Lac des Mille Lacs greenstone belt. Several late mafic to ultramafic intrusions of the Quetico mafic to ultramafic suite are identified and have potential for mineralization with copper, nickel and platinum group metals.

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13. Project Unit 04-016. Reconnaissance Geological Study of Porter and Vernon Townships, Southern Province

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INTRODUCTION

The map area lies 60 km west-southwest of Sudbury, northeast of Agnew Lake, and is underlain by Paleoproterozoic metasedimentary and metavolcanic rocks of the Huronian Supergroup (Southern Province) and Neoarchean granitic rocks (Superior Province). Two weeks of the 2004 field season were devoted to geological mapping and geochemical sampling in Porter and southern Vernon Township, prior to initiation of a detailed mapping program in 2005.

The map area is of interest for several reasons:

1. The area includes mafic intrusive rocks of both the East Bull Lake and the Nipissing intrusive suites which are the subject of ongoing exploration for Cu-Ni-PGE (platinum group elements) mineralization (e.g., the Shakespeare Ni-Cu deposit, Sutcliffe 2003).
2. The area includes skarn mineralization related to contact metamorphism of calcareous rocks of the Espanola Formation by Nipissing gabbro intrusions.
3. The area includes a variety of breccia units, of unknown age and affinity, many of which are localized along faults. The economic and tectonic significance of these breccia units has not been evaluated.
4. Huronian Supergroup rocks in northern Porter and southern Vernon townships have been interpreted to have been deposited in a graben (e.g., Rousell and Long 1998 and references therein). The western margin of the graben lies on the trend of the same fault system that localized the Paleoproterozoic Spanish River carbonatite complex. Other workers (e.g., Mungall and Hanley 2004 and references therein) have suggested that the distribution of the Huronian Supergroup in the area is related to tectonic activity that occurred after the Sudbury impact event. Each interpretation has different implications with respect to mineral potential.
5. Previous geological mapping in the area largely predates establishment of the current Huronian Supergroup stratigraphic framework, hindering interpretation of the existing maps. Access to the area has also improved considerably in recent years.

PREVIOUS WORK

Porter and Vernon townships were mapped as part of the regional mapping of Collins (1938), who first interpreted a graben in the area. Detailed mapping took place in Porter Township in 1956 and 1957 (Ginn 1961) and in southern Vernon Township in 1969 and 1970 (Ward 1972), at scales of 1:12 000 and

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.13-1 to 13-13.

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1:15 840, respectively. Marmont (1986) mapped the north half of Vernon Township at 1:15 840 scale. Ginn (1960) and Fairbairn, Hurley and Pinson (1960) reported several K/Ar ages from Porter Township, mostly from Archean granitic rocks. Many of these K/Ar ages were circa 1260 Ma, not Archean or Paleoproterozoic as might be expected, most likely because many of the samples were collected near Sudbury diabase dikes in the area, which have a U/Pb age of 1238 Ma (Krogh et al. 1987).

RESULTS

Geological Overview

The map area can be divided into 4 geological domains, as illustrated in Figure 13.1. From south to north, these domains are

1. Domain 1. An area south of the Hunter Lake fault that contains metavolcanic and metasedimentary rocks of the Elliot Lake Group and the lower Hough Lake Group, metamorphosed at upper greenschist to amphibolite facies, dominated by east-northeast trends.
2. Domain 2. A faulted domain between the Hunter Lake and South Cygnet faults containing metasedimentary rocks of the Hough Lake and Quirke Lake groups, metamorphosed at lower greenschist facies. These rocks were folded (e.g., Porter syncline) prior to being cut by a series of subparallel, northeast-trending faults. Sudbury breccia is abundant adjacent to and along the major faults.
3. Domain 3. An east-trending domain containing Neoarchean plutonic rocks, metasedimentary rocks of the Hough Lake and Quirke Lake groups and abundant intrusions of Nipissing gabbro. Metamorphism of the Huronian Supergroup is generally at lower greenschist facies, except where contact metamorphosed by Nipissing gabbro intrusions. Broad, east-northeast-trending folds affect all rocks. This domain contains most of the skarn mineralization in the map area. The only known rocks of the East Bull Lake intrusive suite are also found in this domain.
4. Domain 4. This domain underlies the northern one-third of Porter and all of Vernon Township, and contains a north-trending syncline (Vernon syncline, also termed Shiner syncline) of Huronian Supergroup metasedimentary rocks of the Hough Lake, Quirke Lake and Cobalt groups. An outlier of Quirke Lake Group rocks occurs 400 m northeast of the termination of the syncline. Neoarchean granitic rocks bound the Huronian Supergroup strata to the east, west and north. In the north half of this domain, isolated bodies of Nipissing gabbro occur within the area underlain by Neoarchean granitic rocks.

Northwest-trending Sudbury diabase dikes in domains 3 and 4 appear to be continuous for 1 to 3 km along strike, confirming that domains 3 and 4 are less affected by northeast-trending faulting than domains 1 and 2. Highlights of the mapping program fall into 4 main categories, as detailed under the following headings:

1. observations related to Huronian Group "stratigraphy".
2. observations related to "breccia units".
3. observations related to "geophysical properties".
4. observations directly related to "mineralization".

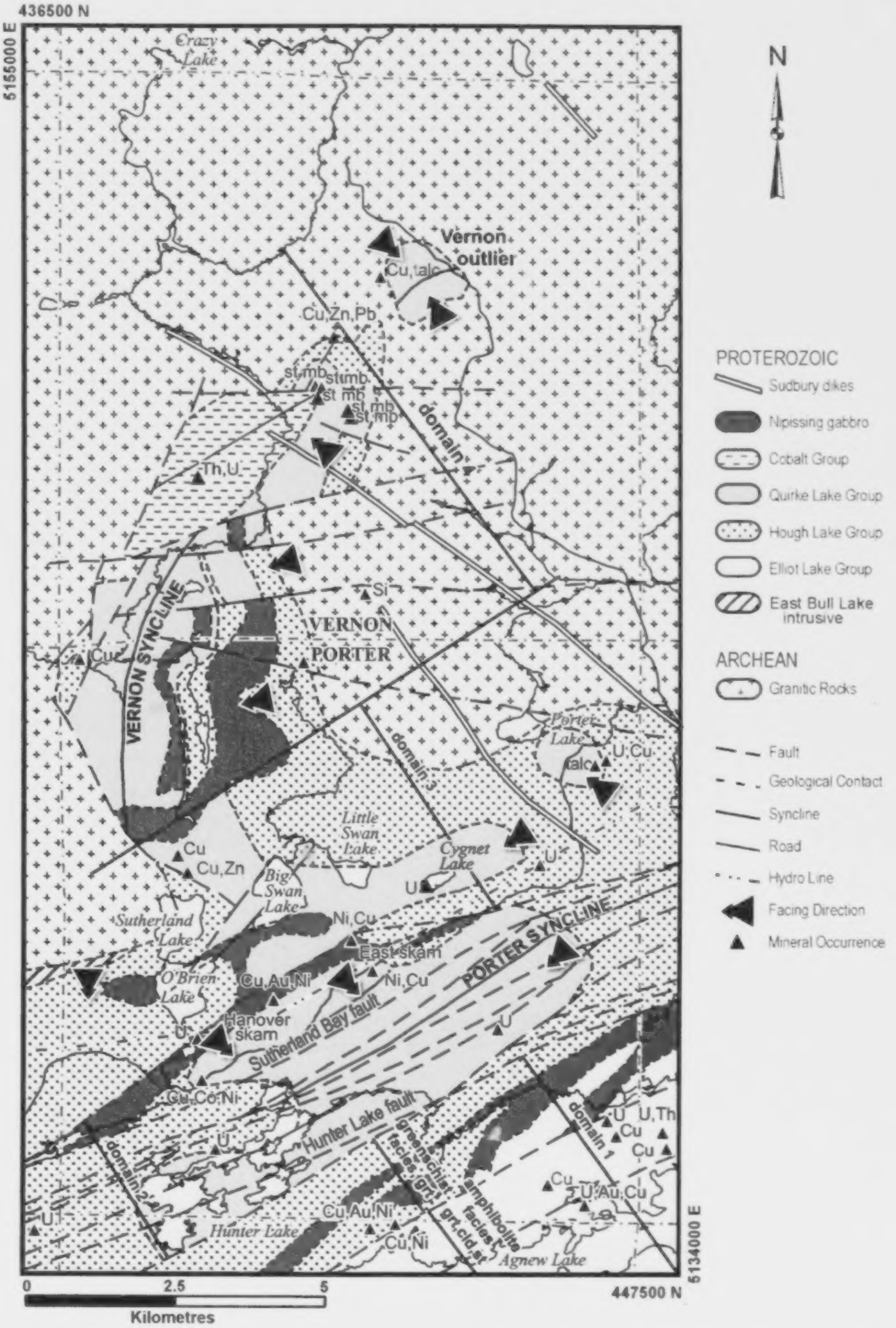
436500 N
5155000 E
Crazy Lake
Vernon outlier
Cu,talc
Cu,Zn,Pb
st,mb
st mb
st mb
st,mb
st,mb
domain 4
Th,U
Si
VERNON
PORTER
Cu
VERNON SYNCLINE
domain 3
Porter Lake
U,Cu
talc
Little Swan Lake
Cygnet Lake
U
U
Cu
Cu,Zn
Big Swan Lake
Sutherland Lake
Ni,Cu
East skarn
PORTER SYNCLINE
O'Brien Lake
Cu,Au,Ni
Ni,Cu
Hanover skarn
U
Sutherland Bay fault
U
Cu,Co,Ni
U
Hunter Lake fault
domain 2
greenschist facies (gr)
greenschist facies
amphibolite facies
grt,cld,st
domain 1
U
U,Th
Cu
Cu
Cu
U,Au,Cu
Cu,Au,Ni
Cu,Ni
Hunter Lake
Agnew Lake
U
5134000 E
447500 N
0
2.5
5
Kilometres
N
PROTEROZOIC
Sudbury dikes
Nipissing gabbro
Cobalt Group
Quirke Lake Group
Hough Lake Group
Elliot Lake Group
East Bull Lake intrusive
ARCHEAN
Granitic Rocks
Fault
Geological Contact
Syncline
Road
Hydro Line
Facing Direction
Mineral Occurrence

Figure 13.1. Simplified geological map of Porter and Vernon townships, indicating the 4 geological domains described in the text, as well as showing known mineral occurrences present in the map area. Arrows indicate generalized stratigraphic facing directions. Mineral abbreviations: Au = gold, Co = cobalt, Cu = copper, Ni = nickel, Pb = lead, si = silica, st mb = stone marble, Th = thorium, U = uranium, Zn = zinc. Adapted *from* Ginn (1961) and Card (1978).

Stratigraphy

The presence of limestone and limestone–siltstone horizons interbedded with siltstone and quartz arenite in the middle to upper Mississagi Formation were observed in an area of excellent outcrop exposure where there is no ambiguity about stratigraphic position. This is the first reported occurrence of limestone in the Mississagi Formation, but it may not be unique; re-examination of diamond-drill core logs from the northern Vernon syncline (Rodgers 1966) also indicates the presence of limestone beds within the Mississagi Formation. This observation means that carbonate sedimentation in the study area occurred both prior to and after Bruce Formation deposition. It also means that in areas of sparse outcrop in Porter and Vernon townships, limestone outcrops cannot be assigned solely to the Espanola Formation. It also raises the possibility that skarn mineralization may be present in the upper Mississagi Formation in association with these limey horizons. Preliminary geochemical results indicate that the trace and rare earth contents of limestone beds from each formation are indistinguishable (Figure 13.2a).

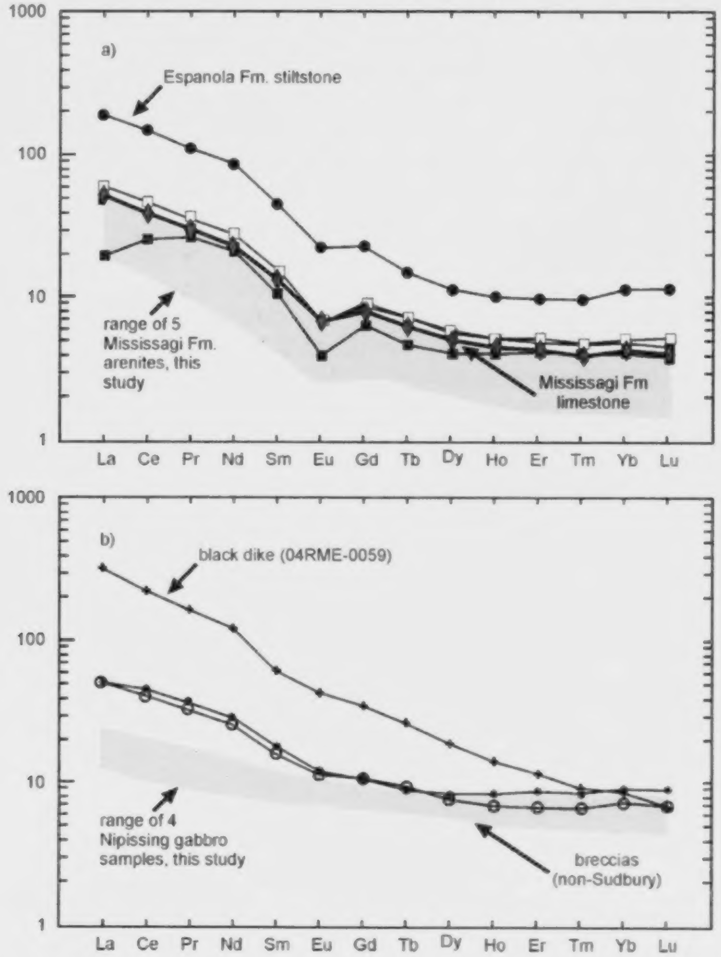

Figure 13.2. A) Chondrite-normalized rare earth element data for Espanola and Mississagi Formation limestones. Range of 5 Mississagi Formation quartz arenites from this study are shown for comparison. Note the similarity between the Mississagi Formation and the Espanola Formation limestones. B) Chondrite-normalized rare earth element data for non-Sudbury breccias at the Hanover skarn and south of Porter Lake, showing similar compositional trends. Black dike (sample 04RME-0059) that may be related to the Spanish River carbonatite complex has much higher light rare earth element contents. Field of 4 Nipissing gabbros from this study are shown for comparision. Note flat rare earth element patterns and no europium anomaly in the Nipissing gabbro samples.

Marmont (1986) reported the presence of an outlier of Huronian Supergroup rocks north of the Vernon syncline, roughly 800 by 400 m in size, composed mainly of siltstone of the Espanola Formation. This outlier is more extensive than first reported (*see* Figure 13.1), covering an area of at least 1000 by 1200 m, and includes rocks of both the siltstone and limestone members of the Espanola Formation and conglomerate of the Bruce Formation. The southwestern limit of the outlier is only 400 m from the northern tip of the Vernon syncline where they are separated by a ridge of Archean granite.

In domains 3 and 4, metasedimentary rocks of the Hough Lake or the Quirke Lake groups appear to lie unconformably on Neoarchean granitic basement, possibly in a transgressive fashion, as higher stratigraphic units mark the unconformity as one heads northward (e.g., Mississagi Formation on Archean at Porter Lake, Espanola Formation on Archean in north-central Vernon Township).

In domain 3, the Espanola Formation limestone member is characterized by a high proportion (50 to 70%) of thin intercalated siltstone beds. In domain 4, the Espanola Formation limestone member is cleaner, with a lower proportion of siltstone beds (<30%), particularly in the middle to upper parts of the limestone member.

Previous interpretations of the stratigraphy at the north end of the Vernon syncline (e.g., Ward 1972; Card 1978) proposed that rocks of both the Matinenda and Ramsey Lake formations were present immediately above the Archean basement. Re-examination of diamond-drill core logs from this area, as well as the regional structural pattern, suggests the presence of a minor fold that refolds rocks of the Mississagi and Bruce formations. This re-interpretation indicates that a thin Mississagi Formation rests directly on Archean basement in the northern Vernon syncline, consistent with the situation in the outlier only 400 m to the north, where Bruce Formation conglomerate and Espanola Formation limestone are in direct contact with Archean basement. It is also consistent with the low radiometric signature of the Huronian Supergroup rocks in domain 4 (Carson et al. 2004a, 2004b, 2004c). This re-interpretation has implications for exploration, as the basal Matinenda Formation is a primary target horizon for uranium mineralization in the Huronian Supergroup. Its apparent absence in domain 4, and probably domain 3, makes these areas less favourable targets for uranium exploration.

Nipissing gabbro bodies appear to have been emplaced at 4 different stratigraphic levels, as follows:

1. at the unconformity with the Archean or solely hosted by Archean strata.
2. within the middle Mississagi Formation. These bodies are both concordant and discordant with geological contacts. The Shakespeare Ni-Cu deposit occurs at this stratigraphic level. Nipissing gabbro from the Shakespeare deposit yielded a concordant U/Pb age of 2217±2 Ma (Sutcliffe 2003), consistent with the known age range of the Nipissing intrusive suite.
3. concordant bodies emplaced at the contact of the Mississagi and Bruce formations.
4. semi-concordant bodies within the Espanola Formation, typically near the Espanola–Serpent formations contact. Skarn mineralization is associated with this intrusion (or intrusions?).

Studies are underway to determine if there is any chemical or textural variations between the gabbro bodies emplaced at these 4 different levels that might be useful in targeting mineralization. Limited whole-rock geochemical data from the Main Skarn on the Big Swan property (Turcott 1997) indicates that, in addition to the presence of a monzonite phase within the Nipissing intrusion, gabbroic rocks at this occurrence have higher SiO_2, TiO_2, K_2O and lower MgO and CaO than typical Nipissing gabbro. Whether this chemistry is unique to this property or to other sills at the same stratigraphic level (within the Espanola Formation) has yet to be determined.

Breccia Units

Marmont (1986), recognized 3 main breccia types immediately north of the map area:

1. Sudbury breccia, including calcareous types,
2. Carbonatitic breccia associated with the Spanish River carbonatite complex, and
3. Heterolithic breccias of uncertain origin.

Carbonatitic breccias have not yet been found in the map area. Sudbury breccia bodies are common, particularly in domain 2 where they occur along major faults. Sudbury breccias are pesudotachylites believed to have formed during fracturing, comminution and melting related to the explosive event that produced the Sudbury structure at 1850±1 Ma (Dressler 1984). Most breccias consist of an aphanitic, siliceous, medium to dark grey matrix, which may be massive, flow banded or vesicular. Fragments are commonly rounded, range in size from less than 1 cm up to 4 m, and include representatives of most rock types mapped in the area except Sudbury diabase. Breccia bodies vary in size from small rootless dikes a few centimetres wide and a few metres long or high, to masses some 15 m wide and 60 m long. The breccias are usually matrix supported. Some Sudbury breccia bodies within the map area are calcareous, with calcite occurring in the matrix, in vesicles, and in recrystallized quartz-feldspar clasts. Magnetic susceptibility readings on Sudbury breccia bodies give average values between 0.5 and 0.9.

At least 3 bodies of heterolithic breccia of unknown origin occur in the map area. In contrast to the Sudbury breccias, these breccias have average magnetic susceptibility readings of 0.1 to 0.2. The first occurs as fragments within Sudbury breccia at the Hanover skarn (439530E 5137222N, NAD 83, Zone 17). Sudbury breccia at this location includes metre-scale fragments of both East Bull Lake and Nipissing intrusive suite gabbros, as well as a variety of other rock types. The nearest surface exposure of East Bull Lake intrusive suite rocks is roughly 3 km to the northwest, thus, it is possible that these fragments originated from a body located beneath the property. Several of the breccia fragments included within the Sudbury breccia consist of a pink-grey weathering, fine-grained, igneous textured intermediate composition rock with possible fiamme and angular, 0.5 to 2 cm intermediate composition rock fragments. At present, this rock has only been observed within Sudbury breccia. It is possible that it may represent an intrusive phase related to the Spanish River carbonatite complex.

The second and third occurrences of heterolithic breccia bodies are located in Huronian Supergroup rocks southeast of Porter Lake, near the unconformity with the Archean basement (445314E 5142226N NAD 83, Zone 17). At this location, a white-weathering, calcareous, clast-supported breccia dominated by subrounded to angular quartz arenite fragments is present. This unit may represent a sedimentary breccia at the unconformity. The breccia is transected by a 25 cm wide, greenish-grey, matrix-supported breccia dike, with angular to subrounded fragments, including gabbroic fragments, that is atypical of Sudbury breccia. The breccia dike may represent an intrusion breccia, perhaps related to the Spanish River carbonatite complex. Preliminary geochemical results indicate that the intrusive breccia at the Hanover skarn and the breccia dike southeast of Porter Lake are distinctive (Figure 13.2b), and have similar contents of large-ion lithophile and high-field strength elements such as Cs, Hf, Nb, Rb, Th, U and Zr, and have a tonalitic bulk-rock composition. Their geochemical affinity to the Spanish River carbonatite complex, however, remains uncertain.

Geophysical Properties

MAGNETISM

Magnetic susceptibility readings on rocks of the Huronian Supergroup in domains 2, 3 and 4 were remarkably uniform, and showed no variation with stratigraphic height or stratigraphic unit. The lowest readings were observed in quartz arenite beds (0.00 to 0.10), the highest readings in mudstone and siltstone beds (0.20 to 0.50). Nipissing gabbro bodies were fairly uniform, with average readings of 0.78, except where the rocks were clearly altered by secondary processes. Sudbury diabase dikes were the only unit to show consistently high readings (25 to 65), however, published regional aeromagnetic maps of the map area are too coarse to allow for mapping of individual Sudbury dikes. This is unfortunate, as these dikes would be very useful in determining offset across major faults, particularly in domains 2 and 3.

RADIOMETRICS

The map area lies at the western limit of a high-resolution gamma-ray spectrometric survey of the Sudbury area (Carson et al. 2004a, 2004b, 2004c). The utility of this survey is limited in Vernon Township because of the greater overburden thickness, but the survey does provide some insight into the geology of Porter Township (Figure 13.3). In general, the area underlain by Huronian Supergroup rocks in both Porter and Vernon townships exhibits low radiometric values for K, U and Th, at least as far north as the northern tip of the Vernon syncline. In contrast, the areas underlain by Archean metaplutonic rocks in the 2 townships exhibit high K, Th, and U values. Nonetheless, there are at least 3 types of gamma-ray spectrometric anomalies in the area underlain by Huronian Supergroup rocks that may be significant with respect to mineral exploration, as illustrated in Figure 13.3.

1. K, U and Th highs (A, Bk and Bu, *see* Figure 13.3).
   One is located northeast of Sutherland Lake, and is underlain by conglomerate of the Bruce Formation (Card 1978); the other is located near Cygnet Lake and is underlain by rocks of the Bruce and Espanola formations. Neither formation typically hosts significant uranium mineralization, but it is possible that the current stratigraphic assignments are incorrect. No known uranium occurrences are reported from the Sutherland Lake anomaly, although there are some Cu-Ni showings on the west flank of the anomaly. The potassium high in the Cygnet Lake anomaly (Bk, *see* Figure 13.3) is centred southwest of Cygnet Lake, but the uranium high (Bu, Figure 13.3) is centred northeast of the lake. Both these areas warrant further exploration for both uranium and skarn mineralization, based on the fact that these are the 2 most intense anomalies present in the area underlain by the Huronian Supergroup. Therefore, they may contain higher grades of uranium mineralization than previously reported from Porter Township (Robertson and Gould 1983).

2. Moderate K highs associated with U highs (C and D, *see* Figure 13.3).
   These anomalies are spatially associated with the East and North Cu-Ni skarn zones, as well as the newly found area of potential skarn mineralization in northeast Porter Township (*see* "Mineralization"). Interestingly, the Hanover skarn is not associated with a K and U high, rather, it is only regionally anomalous with respect to Th/K. Although located at the extreme southwest corner of the survey, it is possible that the Shakespeare Ni-Cu deposit also possesses a similar K and U anomaly. The significance of these anomalies with respect to identifying areas of skarn mineralization is still under investigation, but it does raise the possibility that potassic alteration occurred in conjunction with skarn formation.

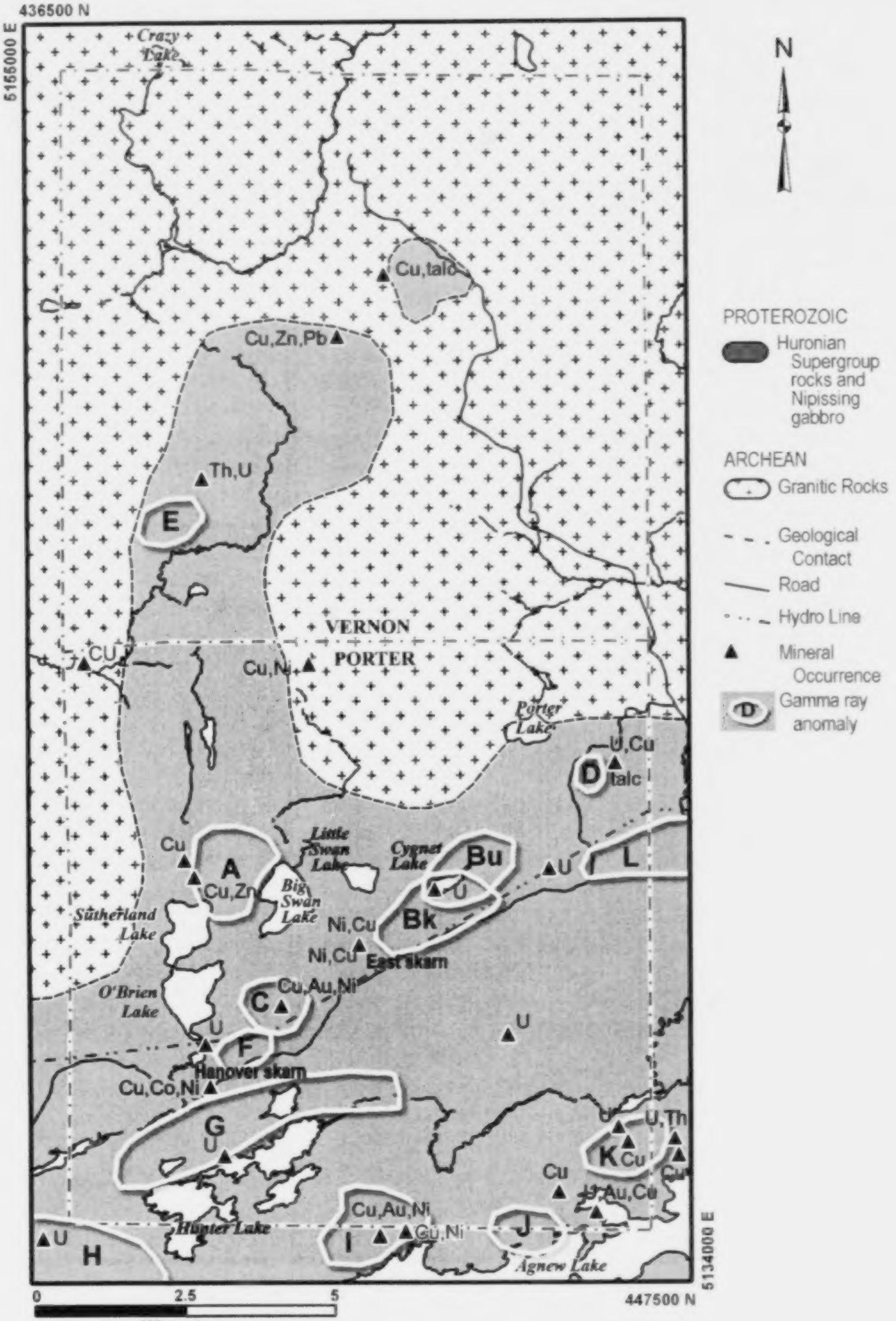
436500 N
5155000 E
Crazy Lake
Cu,talc
Cu,Zn,Pb
Th,U
E
VERNON
PORTER
CU
Cu,Ni
Porter Lake
U,Cu
D
talc
Cu
A
Cu,Zn
Little Swan Lake
Big Swan Lake
Cygnet Lake
Bu
U
U
L
Bk
Ni,Cu
Ni,Cu
East skarn
Sutherland Lake
O'Brien Lake
C
Cu,Au,Ni
U
U
F
Hanover skarn
Cu,Co,Ni
G
U
U
U,Th
K
Cu
Cu
Cu
U,Au,Cu
Cu,Au,Ni
Cu,Ni
I
J
Hunter Lake
U
H
Agnew Lake
5134000 E
447500 N
0
2.5
5
Kilometres
N
PROTEROZOIC
Huronian Supergroup rocks and Nipissing gabbro
ARCHEAN
Granitic Rocks
Geological Contact
Road
Hydro Line
Mineral Occurrence
D
Gamma ray anomaly

Figure 13.3. Location of gamma-ray spectrometric anomalies (highs) in Porter and Vernon townships, as well as the location of previously reported Cu, Ni and U mineralization. Location of the Archean–Proterozoic contact is simplified from Figure 13.1. Mineral abbreviations the same as for Figure 13.1. Letters A to L correspond to anomalies referred to in the text.

Table 13.1. Selected geochemical results from Mississagi Formation samples near anomaly D, Porter Township.

Sample 04RME-	Rock Type	Easting NAD 83	Northing Zone 17	Hf (ppm)	Rb (ppm)	Th (ppm)	U (ppm)	Y (ppm)	Zr (ppm)
0029	Siltstone	445881	5141097	31	216	29	19	16	1148
0053	Arenite	445881	5141097	1	77	4	1	10	48
0122	Siltstone	444859	5141951	14	71	19	10	10	558
0135	Arenite	444859	5141951	3	93	9	3	6	121
All other Huronian Sgp. samples, this study				<5	<70	<9	<4	<8	<275

3. K and U highs, in some cases associated with moderate Th highs (E to L, *see* Figure 13.3). Some anomalies are linear with a northeast orientation. The majority of these highs are underlain by rocks of the Mississagi Formation, near known uranium occurrences. Typically, the known uranium occurrences are located on the flanks of the anomalies, not the centres. The Mississagi Formation does not normally host significant uranium mineralization, consequently the significance of these paired potassium and uranium anomalies is still being investigated.

Two samples of Mississagi Formation siltstone collected for the purpose of geochemical characterization of the formation in the vicinity of anomaly D (*see* Figure 13.3) contained anomalous contents of high-field strength elements that are typically associated with heavy mineral concentrations (samples 04RME-0029 and 04RME-0122, Table 13.1). Adjacent quartz arenite beds (samples 04RME-0053 and 04RME-0135, respectively, *see* Table 13.1) show no such enrichment, even though the quartz arenite beds would be more likely to contain heavy mineral lags. The origin of these anomalous values remains to be determined.

Mineralization

Several areas of Ni-Cu-PGE mineralization have been previously identified in Porter Township, hosted in both Nipissing gabbro and skarn developed in Espanola Formation limestone and siltstone (Table 13.2, also see summary of exploration in Turcott 2002). These include the Hanover, East, Main and Ridge skarns, located immediately north of the hydro line in central Porter Township (*see* Figure 13.1). In addition, Ni-Cu-PGE mineralization has been observed within Nipissing gabbro in contact with Mississagi Formation quartz arenite west-southwest of Sutherland Lake, and in Nipissing gabbro west of O'Brien Lake and in the Bye Zone located at the Porter–Dunlop township boundary. Table 13.2 provides a summary of the best assay results reported from these occurrences, as compiled from the assessment files in the Sudbury Resident Geologist's Office.

A new outcrop area of talc schist was located in Porter Township. The talc schist (sample 04RME-0139, Table 13.3) is associated with a rusty-weathering pyroxene skarn (sample 04RME-0140, *see* Table 13.3), and are both likely the result of contact metamorphism of the Espanola Formation, which occurs in a more pristine condition only a few hundred metres to the north. The pyroxene skarn contains minor quantities of Au, Pd and Pt (sample 04RME-0140, *see* Table 13.3). As noted above, this occurrence lies on the east flank of a moderate K and U airborne gamma-ray spectrometric anomaly and the outer boundary of the anomaly seems to follow the Bruce–Espanola formations contact in this area. Similar anomalies are present in other areas of skarn mineralization in the map area. This anomaly, in conjunction with Marmont's (1986) report of chalcopyrite mineralization in association with talc schist derived from the Espanola Formation in northern Vernon Township, indicates that this new occurrence warrants further examination.

Table 13.2. Summary of Cu-Ni-PGM occurrences hosted in or near Nipissing gabbro in Porter Township.

Name	Easting NAD 83	Northing Zone 17	Reported Values	Assessment File Number
Big Swan Property, Brunne PGM (East skarn)	442214	5139227	8.55 g/t Pd, 11.7 g/t Pt, 0.34 g/t Au, 0.15 wt.% Cu, 0.14 wt.% Ni over 1.0 m	Porter SP-007, SP-011
Big Swan Property, Ridge	441810	5139370	1.48 g/t Pd+Pt+Au, with 1.22 g/t Pd, 0.35 wt.% Cu	Porter SP-007, 011
Big Swan Property, Main skarn	440859	5138646	186 ppb Au, cpy and po present	Porter SP-007, SP-011
Hanover	~439472	5137217	>40 ppb Pd+Pt in soil surveys, grab samples of 713 ppb Au and 224 Pt+Pd+Au	Porter SP-007, SP-011
Porter Grid	~437600	4139040	No assay data reported, cpy and po present	
O'Brien Lake	~437800	5138700	15.6 g/t Pd+Pt. Best grab sample 14 220 ppb Pd, 1439 ppb Pt, 635 ppb Au, 0.28 wt.% Cu.	Porter SP-011, Dunlop SP-007
Bye Zone	~435750	5137450	8.8 g/t Pd+Pt, 7.5 g/t Au. Best grab sample 5439 ppb Pd, 1468 ppb Pt, 735 ppb Au, 1.9 wt.% Cu.	Dunlop SP-007

An outcrop of fractured and hematized, carbonate-altered Nipissing gabbro in central Vernon Township was anomalous in having a high magnetic susceptibility (average values of 30), although an assay of this rock did not reveal any significant metal enrichment (sample 04RME-0079, *see* Table 13.3). Three samples of Nipissing gabbro showing no visible sulphide mineralization, collected from northeast Porter Township in the vicinity of gamma-ray anomaly D (*see* Figure 13.3), were all slightly anomalous with respect to Pd and Pt (samples 04RME-0117, 04RME-0147 and 04RME-0149, *see* Table 13.3). It is possible that all 3 samples are from different parts of the same sill.

D. Brunne (Prospector) has stripped several outcrop areas of Espanola limestone in central Vernon Township and is evaluating these areas as a source of dimension stone. As noted previously, the proportion of siltstone beds in the limestone member is considerably less in domain 4 than in domain 3, which makes domain 4 a better exploration target for this type of stone. One stripped outcrop is of particular interest, in that it contains a medium-grained metadiabase dike, possibly of the Nipissing intrusive suite, cut by a set on *en échelon*, 5 to 10 cm wide, black, magnetic dikes (average magnetic susceptibility of 37, high of 110). The dikes themselves are intensely weathered, and if not for the stripping in this area, they would not likely have been exposed. In the field, they were assigned to the Sudbury dike swarm, but preliminary geochemical results indicates that the black dikes are strongly alkalic in character, with contents of 115 ppm Cs, 10 ppm Hf, 178 ppm Nb, 408 ppm Rb, 10 ppm Ta and a total rare earth element content of 529 ppm (*see* Figure 13.2b). These geochemical characteristics suggest that the dikes are related to the Spanish River carbonatite complex, most likely the pyroxenite phases, based on whole-rock geochemistry (Sage 1987). An assay sample of one of these dikes (sample 04RME-0059, *see* Table 13.3) did not reveal any base or precious metal enrichment.

M. Veirmeir (Prospector) is evaluating a wide (>15 m) quartz vein in south-central Vernon Township as a silica source. This silica prospect is the only mineral occurrence in the map area hosted in Archean rocks.

Table 13.3. Assay results from samples collected in Porter and Vernon townships.

Sample (04RME-)	Rock Type	Easting NAD 83	Northing Zone 17	Au (ppb)	Pd (ppb)	Pt (ppb)	Cu (ppm)	Ni (ppm)
0014	Bruce Fm., minor sulphide	445945	5142908	<6	<2	1.5	39	70
0036	Pyroxene skarn, East skarn	442246	5139202	<6	<2	1	<3	45
0037	Sulphidic pyroxene skarn, East skarn	442242	5139205	<6	<2	<1	243	27
0038	Breccia in Sudbury breccia, Hanover skarn	439530	5137222	<6	<2	2	175	26
0041	Nipissing gabbro block in Sudbury breccia, Hanover skarn	439530	5137222	81	80	71	2640	315
0055	Breccia dike matrix	445314	5142226	<6	<2	2	42	74
0059	Weathered alkalic dike cutting Espanola Fm.	441899	5148485	12	<2	3	120	161
0079	Altered Nipissing gabbro	443236	5150060	<6	3	6	14	68
0085	Nipissing gabbro, non-sulphidic, Porter grid	437576	5139035	9	11	14	103	84
0117	Nipissing gabbro	445099	5142218	8	31	38	157	134
0147	Nipissng gabbro	446353	5142074	<6	31	35	81	124
0149	Nipissing gabbro	446450	5141967	<6	22	32	73	129
0122	Mississagi Fm. siltstone	444860	5141926	<6	<2	1	126	17
0139	Talc schist	446105	5142592	<6	<2	1	<3	28
0140	Pyroxene skarn	446105	5142592	7	18	21	93	168

Discussion

Field observations provide some constraints on the geological history of the area. Deposition of the Huronian Supergroup occurred after 2450 Ma but prior to Nipissing gabbro intrusion at 2220 Ma. Folding of the Huronian Supergroup may have occurred at approximately 2220 Ma, as Nipissing gabbro sills at certain stratigraphic levels are concordant and are folded with their host metasedimentary rocks, whereas other sills are discordant with stratigraphy. This could indicate folding was roughly coincident with Nipissing emplacement. Alternatively, the Nipissing sills may have simply intruded into an already folded sequence. In either scenario, folding occurred at or prior to 2220 Ma. Skarn mineralization occurred in conjunction with sill emplacement. Faulting and thrusting occurred between 2220 and 1850 Ma, likely in conjunction with regional metamorphism to greenschist and amphibolite facies. Faulting and high-grade metamorphism were concentrated in the southern part of the map area. Although not precisely known, it is probable that the Spanish River carbonatite complex and associated north-trending faulting occurred just prior to the 1850 Ma Sudbury event. Sudbury breccia emplacement was localized along pre-existing faults in the area. It is possible that these faults were reactivated after the Sudbury event, in conjunction with the development of the South Range shear zone.

It is premature to evaluate which of the 2 hypotheses regarding the origin of the Vernon syncline is most likely (graben *versus* post-Sudbury event tectonism). Huronian Supergroup rocks in the outlier in Vernon Township, however, show no increase in deformation or increased development of Sudbury breccia at their contact with the underlying Archean basement, as would be expected if they were tectonically emplaced.

RECOMMENDATIONS FOR EXPLORATION

Exploration for skarn mineralization should focus on domains 3 and 4, where Espanola Formation horizons are thickest and most extensive. Areas adjacent to gamma-ray anomalies A, Bk, C, D and F (*see* Figure 13.3) are of particular interest.

Nipissing gabbro sills intruded along and near the Espanola–Serpent Formation contact so far have exhibited the best potential for Ni-Cu-PGE mineralization, and may occur in conjunction with adjacent skarns. Nipissing gabbro sills at this stratigraphic level in the Vernon syncline have not been extensively explored and are a potential target for skarn and Ni-Cu-PGE mineralization.

Exploration for uranium mineralization should focus on gamma-ray anomalies A and Bu (*see* Figure 13.3).

An unanswered question is whether or not Sudbury breccia bodies in the area, particularly along the major fault systems affecting domain 2, have the potential to host offset-dike style Cu-Ni-PGE mineralization. The map area is located only 15 km east of the former Worthington mine, which hosted offset-dike Cu-Ni-PGE mineralization. Furthermore, the major faults in domain 2 represent the intersection of the South Range shear zone and the Murray fault system and, consequently, could have served as conduits for magmas and mineralizing fluids.

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14. Project Unit 04-013. Geology, Tectonic History and Controls on Gold Mineralization in the Western Grimsthorpe Domain, Central Metasedimentary Belt, Grenville Province

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INTRODUCTION

The map area lies east of Highway 62, approximately 35 km southeast of Bancroft and 35 km north of Madoc. It is underlain by Mesoproterozoic supracrustal and intrusive rocks of the Belmont and Grimsthorpe domains of the Central Metasedimentary Belt of the Grenville Province (Easton 1992). The map area covers roughly 200 km^2, is irregular in shape (Figure 14.1), and straddles parts of 4 National Topographic System 1:50 000 sheets, namely 31 C/11, 31 C/12, 31 C/13 and 31 C/14. The area is bounded, approximately, to the north by the Weslemkoon Road, to the east by longitude 77°30′W, to the south by the southern boundary of Tudor and Grimsthorpe townships, and to the west by Highway 62 (*see* Figure 14.1). Roughly 6 weeks of the 2004 field season were devoted to geological mapping and sampling in western Tudor and eastern Grimsthorpe townships.

The map area is of interest for several reasons:

1. The area includes several gold occurrences that have been actively explored since 1989 (Figure 14.2). Despite this activity, the geological base for western Grimsthorpe domain is poor, as is our knowledge on the controls on gold mineralization in this area. A new 1:50 000 scale map of the area will be produced as part of this study.
2. Parts of the map area have been explored for diamonds, most notably by Lydia Diamond Exploration of Canada Limited (*see* Figure 14.2).
3. The map area lies within an area selected by the Ontario Geological Survey for a modern alluvium survey (Reid, this volume), and this project will assist in the interpretation of results from that survey.

PREVIOUS WORK

Tudor and Cashel townships were mapped at 1:31 680 scale by Lumbers (1968, 1969). Meen (1944a, 1944b) mapped Grimsthorpe Township at 1:63 360 scale. Easton and Ford (1994) and Di Prisco, Hammar and Easton (2001) mapped all of Grimsthorpe Township east of longitude 77°30′W at 1:20 000 scale. The area is covered by 1:50 000 scale compilation maps by Lumbers and Vertolli (2000a, 2000b) and Easton (2001a, 2001b). The study area is well endowed with swamps, thick vegetation and moderate till cover, all of which limit outcrop exposure and impair access. A windstorm in August 2002 created a large east-southeast-trending belt of blow down across the central part of the study area, further hampering access. Logging operations since August 2002 have created some access and outcrop exposure in the area of the blow down.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.14-1 to 14-21.

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MINERAL EXPLORATION

The region has had a long history of mineral exploration and prospecting dating back to the 1850s (Lumbers 1969; Carter 1984; Malczak, Carter and Springer 1985), however, only a summary of activity conducted in western Grimsthorpe domain is provided here. Figure 14.2 shows the location of the more significant gold and copper occurrences in the study area. Table 14.1 summarizes the geology of the major occurrences and past producers. Past-producers include the Craig and Gilmour gold mines. The Craig gold mine was discovered in the late 1800s, operated from 1905 to 1906, and underwent some development work between 1934 and 1936 (Lumbers 1969). The Gilmour Mine was opened between 1902 and 1906, and operated intermittently between 1909 and 1936, but has undergone some development work on several subsequent occasions (Malczak, Carter and Springer 1985). From 1989 to 1991, Homestake Mineral Development Company conducted an active gold exploration program over the area from the Skootamatta Forest Access Road to the Moira River (*see* summary in Christie 1990a, 1991). Between 1985 and 2004, exploration activity has occurred intermittently over the Chard–Dillman Tudor Property by several parties (*see* exploration summary in Dillman 2004). Active exploration of this property was occurring in August 2004. Several other prospectors have been active in the study area between 1990 and 2003.

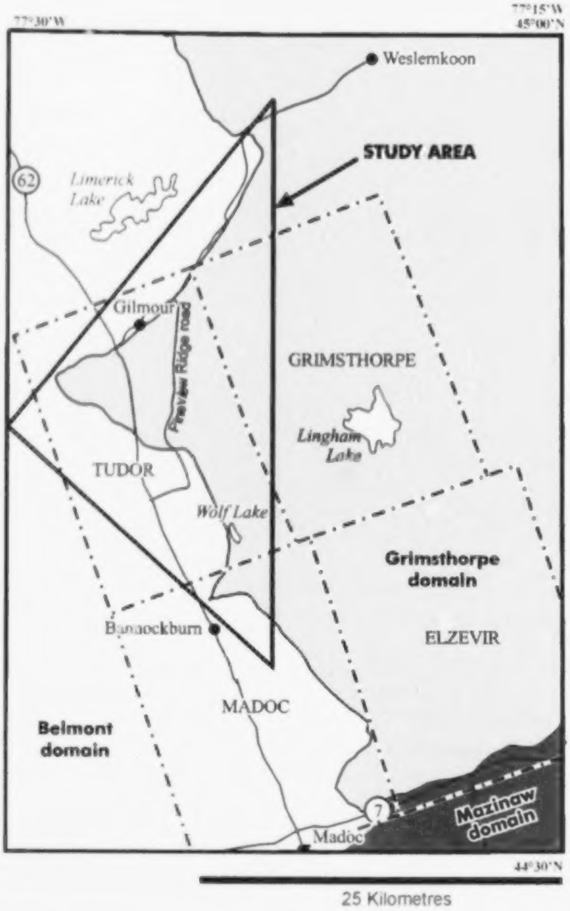
77°30'W
77°15'W
45°00'N
Weslemkoon
STUDY AREA
62
Limerick Lake
Gilmour
Pineview Ridge road
GRIMSTHORPE
Lingham Lake
TUDOR
Wolf Lake
Grimsthorpe domain
Bannockburn
ELZEVIR
MADOC
Belmont domain
7
Madoc
Mazinaw domain
44°30'N
25 Kilometres

Figure 14.1. Location of the study area, indicating the main geological domains mentioned in the text.

Since 1996, gold exploration has been restricted to areas that had been staked prior to the onset of diamond exploration in the area. Diamond exploration, conducted by Lydia Diamond Exploration of Canada Limited, has focussed primarily on 5 areas in Tudor Township (*see* Figure 14.2, and the "Wild Dog" area in Grimsthorpe Township).

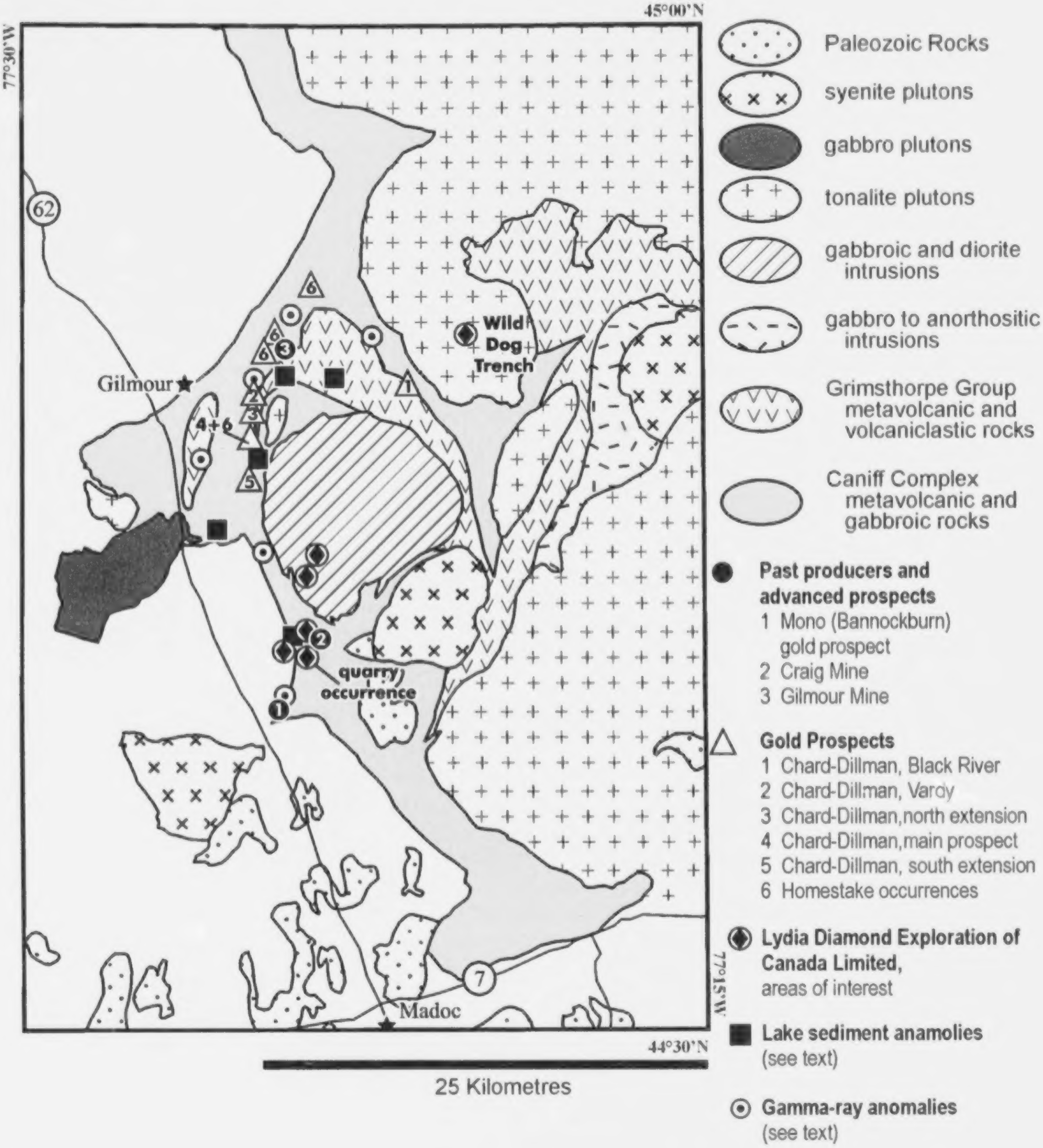
45°00'N
77°30'W
77°15'W
44°30'N
62
7
Gilmour
Madoc
Wild Dog Trench
quarry occurrence
4+6
25 Kilometres
Paleozoic Rocks
syenite plutons
gabbro plutons
tonalite plutons
gabbroic and diorite intrusions
gabbro to anorthositic intrusions
Grimsthorpe Group metavolcanic and volcaniclastic rocks
Caniff Complex metavolcanic and gabbroic rocks
Past producers and advanced prospects
1 Mono (Bannockburn) gold prospect
2 Craig Mine
3 Gilmour Mine
Gold Prospects
1 Chard-Dillman, Black River
2 Chard-Dillman, Vardy
3 Chard-Dillman, north extension
4 Chard-Dillman, main prospect
5 Chard-Dillman, south extension
6 Homestake occurrences
Lydia Diamond Exploration of Canada Limited, areas of interest
Lake sediment anamolies (see text)
Gamma-ray anomalies (see text)

Figure 14.2. Geological sketch map of the study area, showing the location of past-producing gold mines and significance mineral occurrences within western Grimsthorpe domain. Also shown are the location of lake sediment geochemical and airborne gamma-ray spectrometric anomalies discussed in the text. Main areas of exploration work by Lydia Diamond Exploration of Canada Limited are also indicated.

Table 14.1. Summary of major gold and copper occurrences in western Grimsthorpe domain.

Name	Easting Zone 18	Northing NAD 83	Host Rocks and alteration	Style of Mineralization	Best Results	Reference
Black River prospect (Gopher zone)	304971 304826 304036	4966933 4967138 4967433	At contact between Canniff Complex amphibolite and gabbro and Grimsthorpe Group volcaniclastic rocks	Discordant to concordant asp bearing quartz veins, commonly associated with pyritic and carbonatized metabasalt	North zone: 4.1 g/t Au over 0.5 m; Christie zone: 4.6 g/t Au over 0.55m; Gopher zone: 9.2 g/t Au over 0.4 m	Dillman 2003b
Cobalt-Frontenac occurrence	300050	4968250	Schistose, carbonatized metabasalt, minor marble, tourmaline in some veins	Felsite dike?	No details available	Meen 1944a
Craig gold mine	301461	4952973	Amphibolite facies metabasalt at contact of mafic intrusive rocks of Lingham Lake complex	Discordant quartz veins, sulphides rarely contain py, po and cpy	Produced 248 ounces Au, grading 4 g/t Au. Assays from dumps, 0.3-20.2 g/t Au, 100-6500 ppm Cu.	Lumbers 1969; Malczak, Carter and Springer 1985
Chard-Dillman, Tudor Property, Vardy Prospect	297400	4964225	Schistose, carbonatized metabasalt, on strike with Homestake south extension	Concordant to discordant quartz veins and alteration zones with disseminated asp	22.2 g/t Au over 0.5 m. Free gold reported.	Dillman 2004
Chard-Dillman, Tudor Property, North Extension, Main Prospect and South Extension	297700 297275 297250	4963875 4962925 4962100	Mylonitized felsite hosted in schistose, carbonatized metabasalt and metasedimentary rocks	Concordant to discordant quartz veins and alteration zones with disseminated asp	North: 0.2-9.7 g/t Au; Main: 0.5-75.4 g/t Au; South: 1.29 to 2.58 g/t Au	Dillman 2004
Gilmour gold mine	299561	4968673	Schistose, carbonatized metabasalt, tourmaline in some veins	Concordant to discordant quartz and quartz-ankerite veins	Produced 1178 ounces Au, grading 9.6 g/t Au. Trench assays: 8.4-14.3 g/t Au. Rock dump: 0.3-13.7 g/t Au. Mill tailings: 35.5 g./t Au, 1360 ppm Cu, 1500 ppm As. Free gold reported.	Malczak, Carter and Springer 1985
Hodgson occurrence	~297400	4958350	Schistose, carbonatized metabasalt	No details available	136-2776 ppb in soils	Hodgson 2000
Homestake north zone	~299700	4970450	Schistose, carbonatized metabasalt	No details available	3.6 g/t Au over 1.6 m	Christie 1991
Homestake middle zone	~297450	4968550	Schistose, carbonatized metabasalt	No details available	7.3 g/t over 0.95 m, 5.7 g/t Au over 1 m. Free and visible gold in drill core.	Christie 1990b
Homestake south extension	~29800	4967300	Schistose, carbonatized metabasalt	No details available	1.1 g/t Au over 3.3 m, includes 2.1 g/t Au over 1.3 m	Christie 1991
Laidlaw-Beesley occurrence	304000	4966725	Schistose, carbonatized metabasalt	No details available	0.5 g/t Au over 0.86 m to 1.06 g/t Au over 0.28 m	MDI 31C1400026

Table 14.1, continued.

Name	Easting Zone 18	Northing NAD 83	Host Rocks and alteration	Style of Mineralization	Best Results	Reference
Laidlaw occurrence	298300	4964750	Schistose, carbonatized metabasalt	No details available	367 ppb Au from channel sample, 445 ppb Au from grab sample	MDI 31C1300129
McMurray occurrence	297623	4970523	Rusty schist, metabasalt, secondary magnetite	Concordant to discordant quartz and quartz-ankerite veins, py, po and minor cpy in schists, asp in metabasalts near veins	8.4 g/t Au over 0.45 m	Lumbers 1969; Malczak, Carter and Springer 1985
Mono prospect (also termed Bannockburn gold prospect which is near, but distinct from the Bannockburn gold mine	298000	4947000	Folded contact between rusty schists and altered metabasalt and metagabbro. May related to syenite pluton at depth.	345° to 360° trending, 45° east dipping quartz-ankerite veins with bluish quartz. Py, po, asp. Visible gold in drill core and exposed veins	"reserves" of 225 000 tonnes at 9.16 g/t Au in 1992	LeBaron 1991, LeBaron et al. 1993
Quinlan Lake occurrence	302500	4952400	Amphibolite facies metabasalt	Quartz vein, asp, py, tour	2.5 g/t Au	Lumbers 1969
Quarry occurrence	29850	4951370	Schistose, carbonatized metabasalt	Concordant to discordant quartz, quartz-tourmaline and quartz-ankerite veins, asp	No details available	This study
Snow Road occurrence	295250	4962300	Schistose, carbonatized metabasalt and metagabbro, tourmaline clots and secondary magnetite in host rocks	Concordant to discordant quartz and quartz-ankerite veins, py	Trace Au, Ag	Lumbers 1969
Tipperary occurrence	299300	4960600	Lingham Lake complex	Asp-bearing quartz veins	Grab samples of 13.4 g/t and 4.1 g/t Au	Meen 1944a, MDI 31C1300108
Tudor Twp., Concession 10, lot 1	297950	4959800	Diorite, Lingham Lake complex	Quartz vein with asp, py	Trace Au, Ag	Lumbers 1969
Tudor Twp., Concession 14, lot 4	297450	4963900	Felsite	Asp, py, cpy in mylonitic felsite	Trace Au, Cu, Ag	Lumbers 1969
Moira River and England occurrences, Tudor Twp., Concession 13, lot 5	297100	4963650	Felsite, and schistose, carbonatized basalt, tourmaline in some veins	Asp, py, cpy in quartz vein cutting mylonitic felsite.	Vein 0.3 g/t Au. Asp rock 0.9 g/t Au. Grab samples of 0.9 to 1.8 g/t Au	Lumbers 1969; Malczak, Carter and Springer 1985
Tulonen-King occurrence	298400	4955400	Rusty schist, carbonate altered metavolcanic rocks, possible SEDEX deposit?	No details available	1-35% graphite, 97 to 14,925 ppm Zn over 1.5 m, 110 to 930 ppm Cu	Tulonen and King 1999

Abbreviations: asp = arsenopyrite, cpy = chalcopyrite, po = pyrrhotite, py = pyrite, tour = tourmaline.

RESULTS

Geological Overview

As noted previously, the map area straddles 2 geological domains of the Central Metasedimentary Belt, namely, Belmont and Grimsthorpe, with the study focussing on Grimsthorpe domain (*see* Figure 14.1). Figure 14.3 is a geological sketch map of the study area and surroundings, showing the major geological units present.

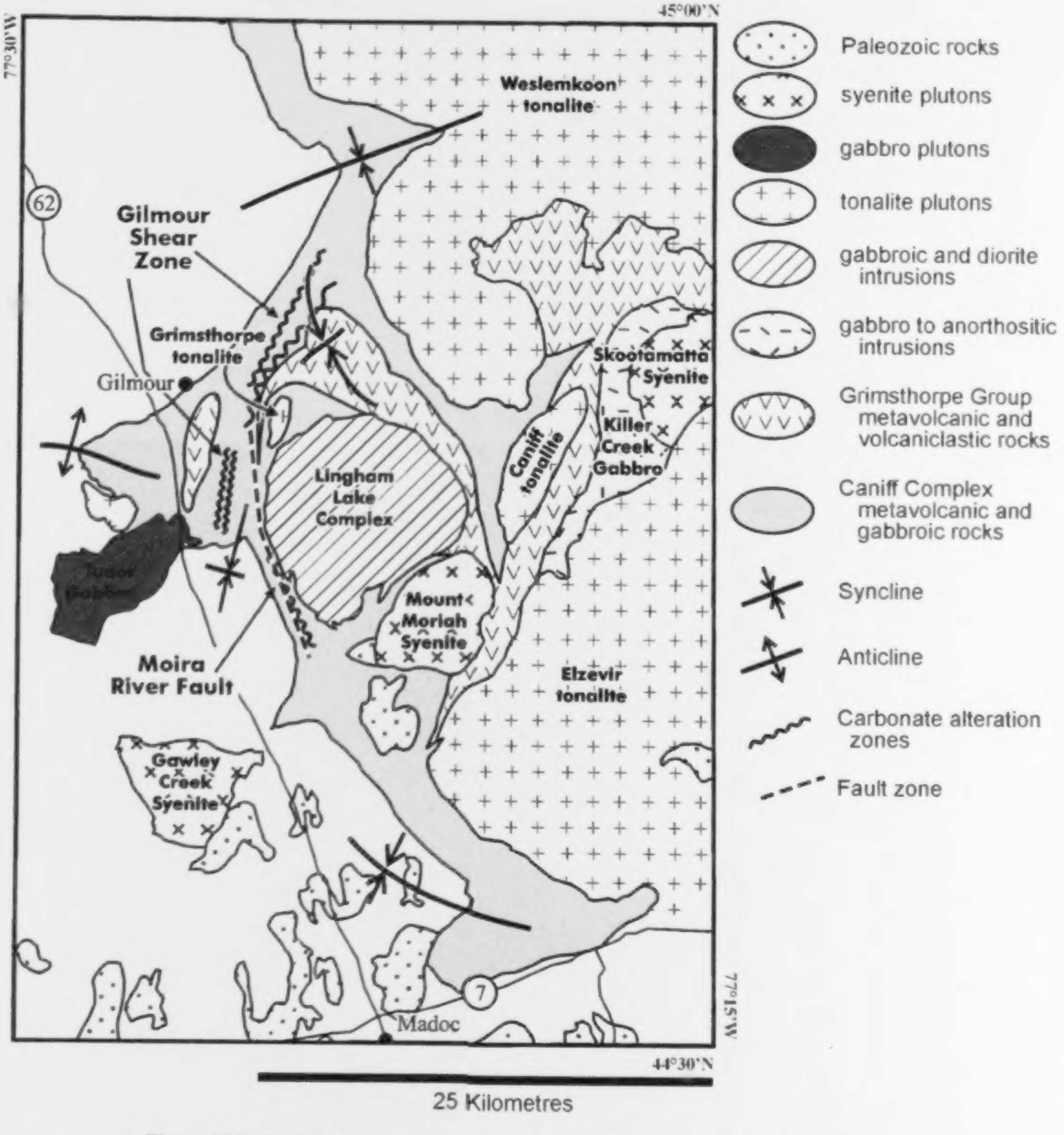
45°00'N
77°30'W
77°15'W
44°30'N
Weslemkoon tonalite
Gilmour Shear Zone
Grimsthorpe tonalite
Gilmour
62
Lingham Lake Complex
Tudor Gabbro
Skootamatta Syenite
Killer Creek Gabbro
Caniff tonalite
Mount Moriah Syenite
Moira River Fault
Elzevir tonalite
Gawley Creek Syenite
7
Madoc
25 Kilometres
Paleozoic rocks
syenite plutons
gabbro plutons
tonalite plutons
gabbroic and diorite intrusions
gabbro to anorthositic intrusions
Grimsthorpe Group metavolcanic and volcaniclastic rocks
Caniff Complex metavolcanic and gabbroic rocks
Syncline
Anticline
Carbonate alteration zones
Fault zone

Figure 14.3. Geological sketch map of the study area, showing major geological features.

RESULTS

Geological Overview

As noted previously, the map area straddles 2 geological domains of the Central Metasedimentary Belt, namely, Belmont and Grimsthorpe, with the study focussing on Grimsthorpe domain (see Figure 14.1). Figure 14.3 is a geological sketch map of the study area and surroundings, showing the major geological units present.

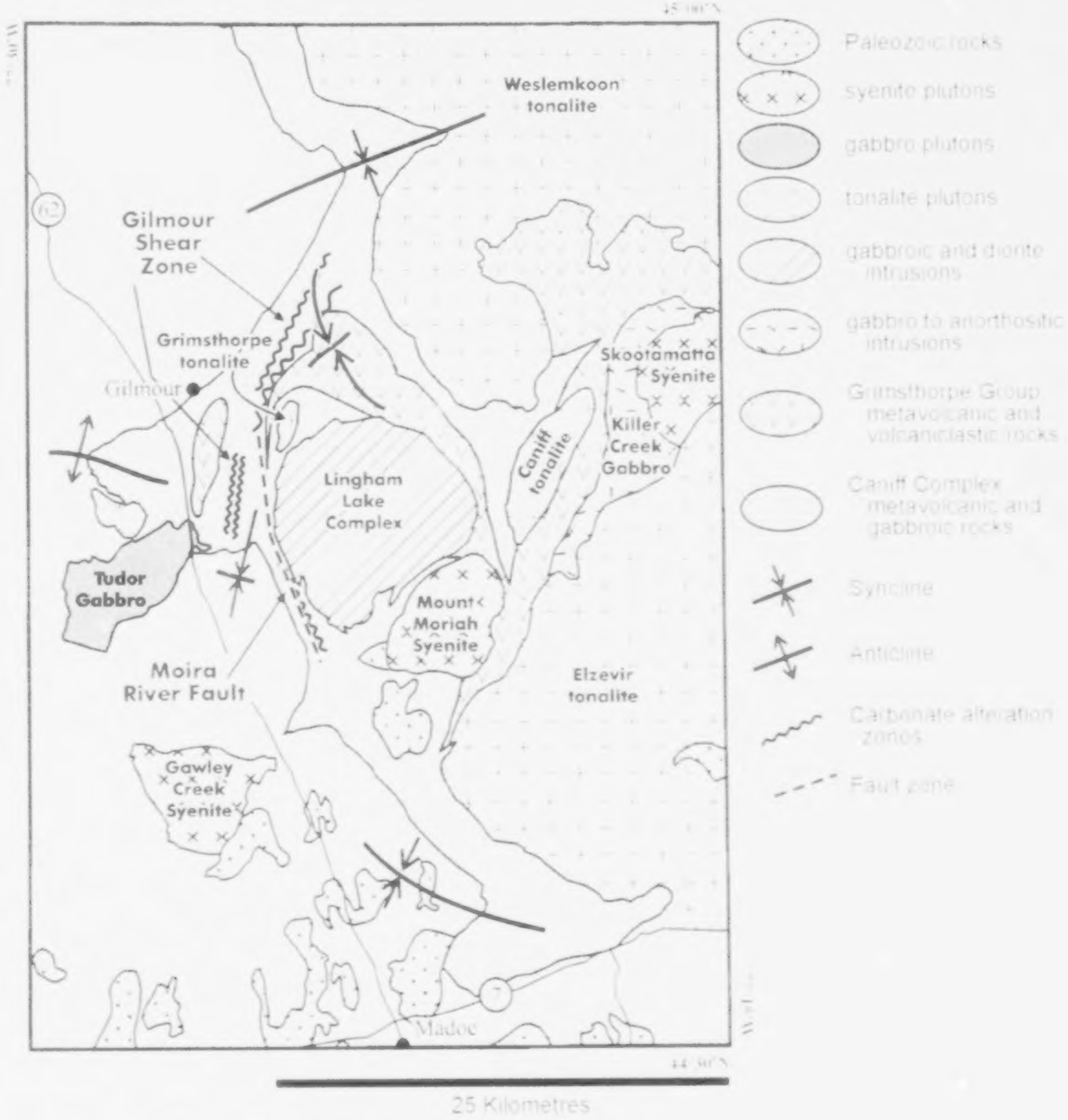
45°00'N
Weslemkoon tonalite
62
Gilmour Shear Zone
Grimsthorpe tonalite
Gilmour
Lingham Lake Complex
Caniff tonalite
Skootamatta Syenite
Killer Creek Gabbro
Tudor Gabbro
Mount Moriah Syenite
Moira River Fault
Elzevir tonalite
Gawley Creek Syenite
7
Madoc
44°30'N
25 Kilometres
Paleozoic rocks
syenite plutons
gabbro plutons
tonalite plutons
gabbroic and diorite intrusions
gabbro to anorthositic intrusions
Grimsthorpe Group metavolcanic and volcaniclastic rocks
Caniff Complex metavolcanic and gabbroic rocks
Syncline
Anticline
Carbonate alteration zones
Fault zone

Figure 14.3. Geological sketch map of the study area [illegible]

The Belmont domain consists of at least several discrete packages of bimodal metavolcanic rocks, ranging in age from 1285 to 1250 Ma, as well as siliciclastic and carbonate metasedimentary rocks. These rocks are intruded by mafic (Lavant intrusive suite) and granitic (Methuen intrusive suite) plutons at circa 1245 Ma (Easton 1992). Metamorphic grade in the Belmont domain, particularly the southern and eastern parts of the domain, is low, ranging from middle greenschist to lower amphibolite facies. Adjacent to the study area, the Belmont domain consists mainly of grey, thin-bedded, calcite marbles with interbedded metasiltstone and locally metasandstone.

In contrast, the Grimsthorpe domain is dominated by mafic, metavolcanic and volcaniclastic metasedimentary rocks that are older than 1270 Ma. Carbonate metasedimentary rocks are rare. Plutonic rocks are dominated by tonalite and granodiorite plutons of the Elzevir intrusive suite. Metamorphic grade in the Grimsthorpe domain ranges from lower to middle greenschist facies in the south and east parts of the domain, to amphibolite facies in the north (Easton 1992).

Stratigraphy

Easton (1992) and Easton and Ford (1994) recognized 2 major supracrustal packages within the eastern part of Grimsthorpe domain, as follows, from youngest to oldest:

- *Grimsthorpe Group:* Metasedimentary rocks derived from a mafic volcanic and gabbroic source region, minor metabasalt flows. Main rock types are matrix- and clast-supported metaconglomerate, gabbro cobble metaconglomerate, meta-arenite, metawacke, minor metasiltstone, metapelite, rusty schist. Minor pillowed and massive tholeiitic metabasalt flows.

unconformity?

- *Canniff Complex:* Massive and pillowed tholeiitic metabasalts, spilitic metabasalts; protomylonitic metagabbro and metaperidotite. Ultramafic rocks commonly altered to talc ± anthophyllite ± actinolite rocks.

A U/Pb zircon age of 1279±3 Ma (Heaman et al. 1987) from a felsite within the Grimsthorpe Group in Tudor Township provides a minimum age of deposition for both the Canniff Complex and the Grimsthorpe Group. Both the Grimsthorpe Group and the Canniff Complex are intruded by a variety of younger plutonic rocks (*see* Figure 14.3). These include

1. ultramafic, gabbroic and anorthositic rocks of the Killer Creek intrusive suite (>1270 Ma, Easton 1992)
2. gabbroic and dioritic rocks of the Lingham Lake intrusive complex
3. tonalitic and granodioritic rocks of the Elzevir intrusive suite, dated at circa 1270 Ma (Heaman et al. 1987). These include the Grimsthorpe, Canniff, Weslemkoon and Elzevir intrusions.
4. gabbroic rocks of the Lavant intrusive suite, which were emplaced at circa 1240 to 1250 Ma (Easton 1992). The Tudor gabbro is the largest body of this suite in the study area.
5. syenitic rocks of the Kensington-Skootamatta suite, which were emplaced at circa 1075 to 1090 Ma (Easton 1992). Both the Mount Moriah syenite and the Skootamatta syenite intruded supracrustal rocks of Grimsthorpe domain.

There are several notable differences between the eastern and western Grimsthorpe domains. The Grimsthorpe Group in the west contains a higher proportion of metavolcanic rocks (Tudor Formation) than in the east, and mafic rocks of both the Canniff Complex and the Grimsthorpe Group in the western Grimsthorpe domain are more extensively altered than they are in the east. In addition, primary volcanic and sedimentary textures are less commonly observed in supracrustal rocks in western Grimsthorpe domain.

Rare, grey, fine-grained dolomite horizons, some of which were mapped by Meen (1944a, 1944b), occur in association with metasedimentary rocks of the Grimsthorpe Group, and may represent exhalative deposits. There may also be more felsite horizons in the western Grimsthorpe domain. It remains to be determined if these felsites are felsic flows or tuffs intercalated with the mafic volcanic rocks or if they are simply fine-grained, deformed, intrusive rocks. The Canniff Complex in western Grimsthorpe domain is dominated by metabasaltic rocks, with a minimal amount of metagabbroic or metaperidotitic rocks.

Alteration, the poor preservation of textures, and the lack of marker units makes stratigraphic mapping difficult in eastern Grimsthorpe domain. As illustrated in Figure 14.3, however, metamorphosed volcaniclastic rocks of the Grimsthorpe Group occur mainly in the area between Highway 62 and Pine View Ridge road, and north of the Lingham Lake intrusive complex. Canniff Complex rocks occur mainly in a 0.5 to 1.5 km belt around the margins of the Lingham Lake intrusive complex. Lumbers (1969) regarded the amphibolites of the Canniff Complex to be the result of contact metamorphism. Easton and Ford (1994), based on the intensity of deformation in these rocks and their association with older mafic and ultramafic rocks, regarded the amphibolites as part of an older rock package that was exposed due to uplift along the margins of the Elzevir suite intrusions. The latter interpretation is reinforced by observations from the study area that the Lingham Lake intrusive complex cuts across Canniff Complex amphibolites that are affected by intense carbonate alteration. There is no difference, however, in alteration style or mineralogy proximal to the intrusion, as would be expected if an intense contact aureole was present.

A variety of fine-grained, but commonly plagioclase porphyritic, mafic dikes cut the mafic metavolcanic and metasedimentary rocks of the western Grimsthorpe domain. These dikes are likely related to the Lingham Lake intrusive complex, based on composition and the fact that plagioclase-phyric intrusive phases are abundant in the western part of the complex. Furthermore, dike abundance increases with proximity to the complex, and the dikes are generally less affected by carbonate alteration and deformation than their host rocks.

Alteration Zones and Vein Systems

Alteration of the mafic metavolcanic rocks of both the Grimsthorpe Group and the Canniff Complex is complex, and ranges from minor to intense. The dominant form of alteration is the introduction of whitish to buff calcite and dolomite, brown to red-brown weathering ankerite, and quartz into the metavolcanic rocks. This occurs in a variety of forms:

1. Along thin (1 to 10 mm wide) carbonate ± quartz veins injected along fractures. Vein spacing may be on the order of tens of centimetres, but typically is on the order of 1 or 2 cm. Veins may be continuous or discontinuous along strike.
2. A more pervasive introduction of carbonate, generally accompanied by the development of chlorite, white mica and/or biotite along cleavage surfaces. Rocks become highly schistose, and weathered surfaces may appear pocked, due to recessive weathering of large carbonate grains.
3. An almost complete replacement by red-brown carbonate, producing a fairly massive rock that no longer resembles an igneous rock (Photo 14.1). Associated with these zones are biotite-rich (>15%) horizons. Quartz veins and pods, typically disrupted, are commonly associated with these zones of intense alteration.
4. Some of the schistose, carbonated metavolcanic rocks develop a fine, mylonitic lamination that is commonly crenulated. It is unclear if this texture represents a mylonitized metavolcanic rock

that was subsequently subjected to carbonate alteration, or if the mylonitization occurred in conjunction with alteration.

5. Epidote alteration is associated with some of the quartz-carbonate veins, particularly the more discordant veins (Photo 14.2). Epidote alteration is more commonly observed in the northern part of the study area.

When first introduced, carbonate is white, grey or buff-coloured calcite or dolomite. With increasing deformation and introduction of carbonate, buff and brown dolomite and ankerite are the dominant carbonate minerals. In the most intensely carbonate-altered zones red-brown ankerite is the dominant carbonate mineral. Colour of the non-carbonate portions of the altered mafic rocks can vary considerably, from dark green to pale green or blue green. There seems to be no systematic pattern of colouration with respect to vein type or degree of alteration or primary host rock material.

Locally within the alteration zones, secondary magnetite develops throughout the altered rocks, forming large, randomly distributed grains (Photo 14.3). Magnetic susceptibility measurements from these zones range from 30 to 200, and various magnetite occurrences and magnetic anomalies previously reported from the area (e.g., Lumbers 1969; Ontario Geological Survey 2002) are likely related to these zones of secondary magnetite development. In some instances, thin (5 to 15 mm) veins of magnetite are observed. The development of the magnetite appears to occur after alteration and deformation is complete, and may be a product of regional metamorphism. Two different prograde reactions could be responsible for this magnetite growth (Bucher and Frey 2002). Epidote breakdown will release Fe^{3+}, which would then become available to form magnetite. Alternatively, chlorite and hematite can react to form the assemblage chloritoid-magnetite-quartz. It is unlikely, however, that this reaction would produce the quantity of magnetite observed in most outcrops.

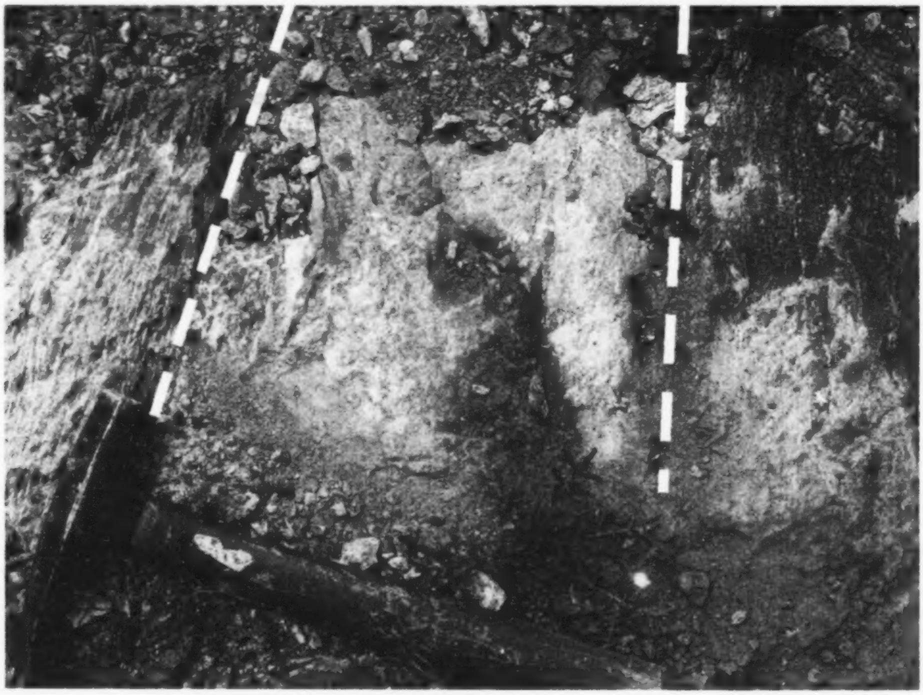

Photo 14.1. Carbonate alteration in mafic metavolcanic rock of the Grimsthorpe Group, ranges from minimal (right), to intense (left), to complete (centre). Hammer handle is 30 cm long. Station 04RME-0506, 296514E, 4960814N, Zone 18, NAD 83.

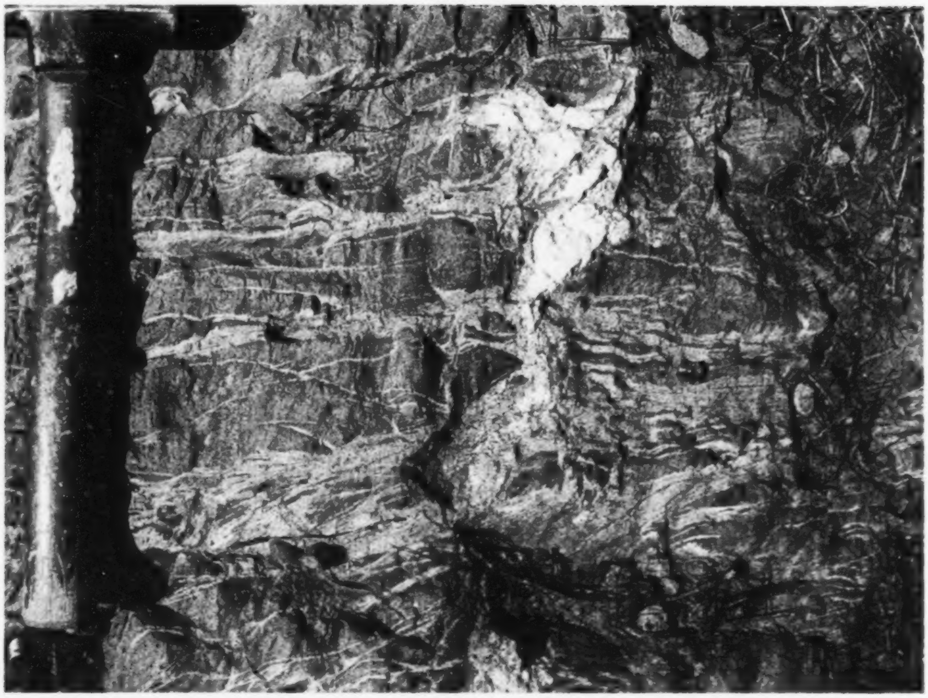

Photo 14.2. Chlorite and epidote replacement (light grey) along fractures in altered mafic metavolcanic rocks of the Canniff Complex. Note irregular shaped quartz vein in centre of photograph. Epidote alteration zones trend 070°/75°, quartz vein trends 190°/75°. Hammer handle is 30 cm long. Station 04RME-0437, 300432E, 4968195N, Zone 18, NAD 83.

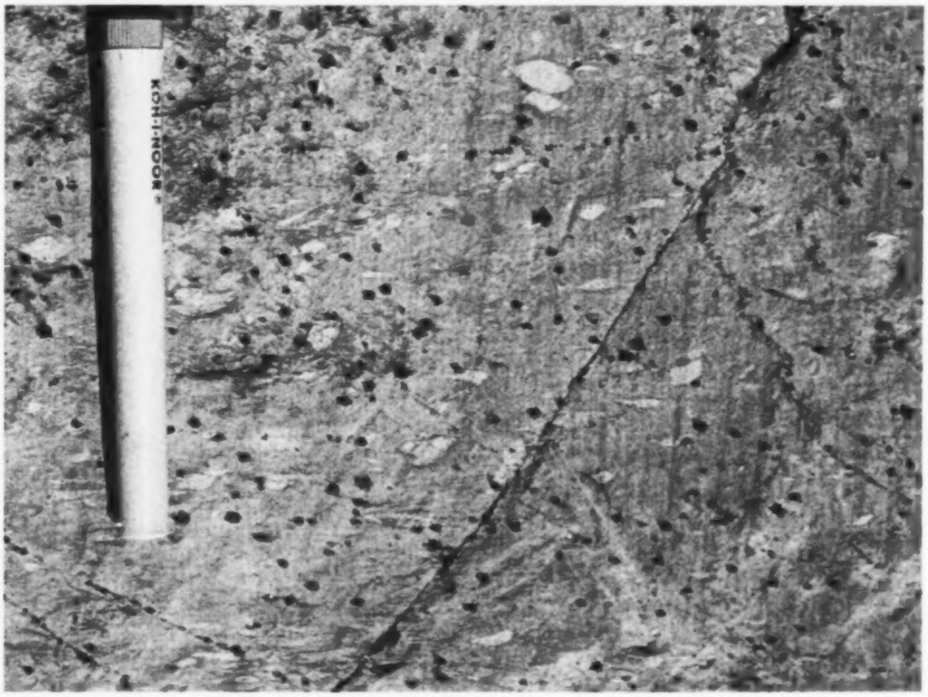

Photo 14.3. Secondary magnetite (dark spots) in mafic lapilli tuff of the Grimsthorpe Group Pen handle is 9 cm long. Station 04RME-0489, 295664E, 4961075N, Zone 18, NAD 83.

Quartz vein systems show a variety of forms as well, in part, likely reflecting the fact that these veins developed over a period of time during regional alteration and deformation. Older veins tend to be foliation parallel, thinner (<1 cm), and may be discontinuous or boudinaged. Quartz in the older veins tends to be more sugary in texture. In extreme cases, larger veins are completely broken up producing rocks full of elliptical-shaped quartz clots. Younger veins are commonly wider (1 to 10 cm) and semi-concordant or discordant to fabric. Quartz in these veins can be sugary, but more commonly is white to glassy. Quartz and quartz-carbonate veins of any age are commonly accompanied by sulphide minerals, which may occur in, or adjacent to, the veins. Arsenopyrite tends to be the dominant sulphide mineral found in association with the veins, but pyrite and chalcopyrite are also common. Vein systems in mafic dikes cutting the altered mafic metavolcanic rocks tend to be dilatant fracture fillings that develop perpendicular to the dike margins, and which do not extend across the dike margins into the host rocks. In the northern part of the area, chlorite is a common accessory mineral in some veins. In the southern part of the area, particularly in the vicinity of the quarry occurrence, tourmaline is a common accessory mineral. Veins that are clearly hosted by Canniff Complex amphibolites, such as at the Craig Mine, are quartz dominated, and contain much less carbonate than veins hosted in Grimsthorpe Group rocks.

Alteration of felsite bodies hosting gold mineralization is somewhat different in character, in that carbonate alteration is minimal. Instead, alteration consists of disseminated arsenopyrite associated with friable, schistose and chloritic zones in the felsite, as well as zones of discrete, concordant to semi-concordant quartz veins with associated arsenopyrite. Mineralization is associated with the development of a protomylonitic fabric in the felsite. Immediately south of the Chard–Dillman south extension, new exposures across the felsite unit show the development of an intense mylonitic fabric, alteration zones, and quartz veining on the west side of the body, with the intensity of alteration and deformation dropping off rapidly to the east. On the east side of the body, the felsite exhibits a more igneous-like texture, and appears originally to have been to be a fine-grained tonalite to granodiorite.

The zones of alteration and extensive quartz veining are anastomosing, particularly in the northern part of the map area. On a property scale, this makes it difficult to trace some of the more intense alteration and mineralized zones along strike. As noted by Christie (1990a), at least 2 main fabrics are present in the alteration zones: an early, steep fabric with associated quartz veins and azimuths of 250° to 220°; and a younger, steep, fabric oriented 170° to 180° and closely associated with carbonate flooding. Late, discordant quartz veins commonly also exhibit a 250° to 220° orientation. Tight to isoclinal folds with 180° axes are common, folding the earlier fabric and early quartz veins and stringers (Photo 14.4).

Notable exceptions to the anastomosing character of the alteration zones are 2 zones on either side of the north-trending portion of the Moira River (Moira River fault zone of Lumbers 1969), where the alteration zones are more linear and continuous, and exhibit abundant carbonate flooding. At least 2 discrete zones, both dominated by strong 170° to 180° steep-dipping fabrics, are present; a previously unrecognized zone about 300 m west of the Moira River, and a second zone along the east bank of the Moira River, which may extend continuously from west of the Chard–Dillman prospects, through the Hodgson occurrence, to the Quarry occurrence (*see* Figure 14.2). The zone west of the river commonly contains intensely mylonitized mafic metavolcanic rocks (e.g., *see* Photo 14.4), particularly on its eastern flank. In addition, the zone west of the river appears to be truncated at the Belmont–Grimsthorpe domain boundary, as there is no evidence of deformation or alteration of the low-grade Belmont domain marbles directly on strike with the trace of the alteration zone. This suggests that the alteration and veining occurred before development of the domain boundary.

The alteration zone east of the river is truncated in places by porphyritic monzodiorite of the Lingham Lake intrusive complex, and locally includes inclusion-breccias containing carbonate-altered metavolcanic fragments. This suggests that alteration and veining was largely complete by the time of intrusion of the Lingham Lake intrusive complex. This raises the question of the origin and timing of quartz veins present within the Lingham Lake intrusive complex, some of which have associated trace gold and arsenic mineralization (*see* Table 14.1; Lumbers 1969). In one locality, the author observed a large, partly digested inclusion of altered, quartz-veined metavolcanic rock within biotite diorite of the Lingham Lake intrusive complex roughly 1.5 km inward from the western margin of the body. Thus, in some cases, the veins may be related to remnant metavolcanic pods within the complex. In addition, quartz veins commonly occur along both north- and east-trending late fault systems in this part of the Central Metasedimentary Belt, and some of the veins reported from the Lingham Lake intrusive complex may be related to these younger fault systems. Regardless of origin, to date, only low-grade gold and arsenic mineralization has been reported from vein systems located within the Lingham Lake intrusive complex (e.g., Lumbers 1969; *see* also Table 14.1).

Faults and Shear Zones

Lumbers (1969) noted 2 fault systems in the area: a north to northeast system and a northwest system. He identified a fault of the north-northeast system along the Moira River, which he termed the Moira River fault. He noted that the major faults in the area, such as the Moira River fault, are actually fault zones, which transpose earlier fabrics, result in shearing, mylonitization and the development of quartz vein networks. Christie (1990a) subsequently introduced the term Moira River shear zone, which included the Moira River fault of Lumbers (1969), but extended it to the northeast, by including northeast-trending alteration zones in the vicinity of the Gilmour mine.

There are probably at least 2 separate, but distinct, structures along the Moira River. The earlier structure, which has a northeast orientation, consists of the alteration and deformation zones of the Moira

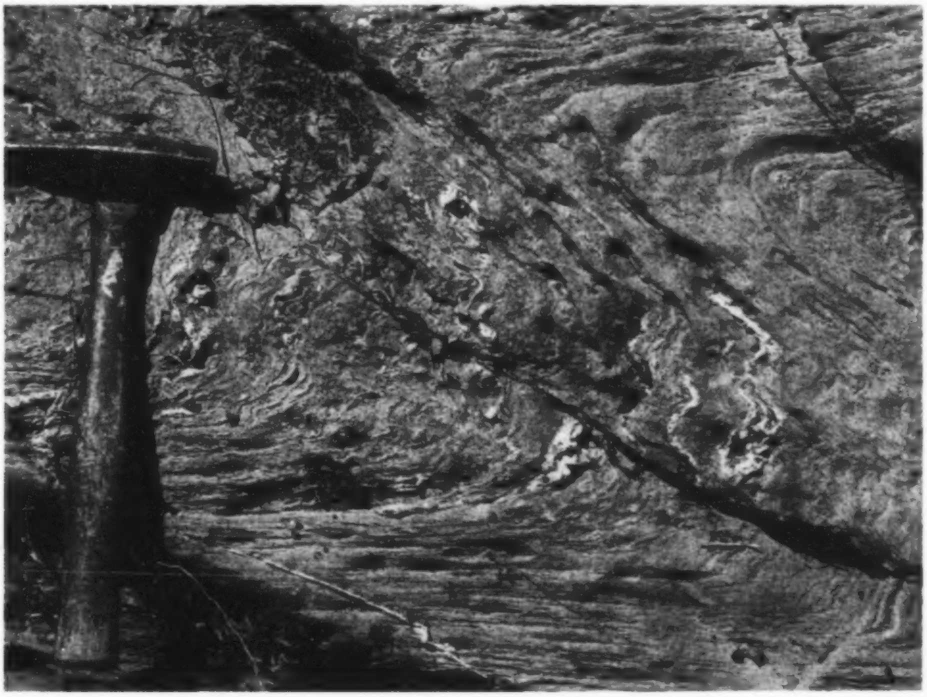

Photo 14.4. Tight folds developed in mylonitic mafic metavolcanic rock of the Grimsthorpe Group. Note folding and tectonic disruption of early, foliation parallel quartz veins and stringers. Hammer handle is 30 cm long. Station 04RME-0583, 296752E, 4958533N, Zone 18, NAD 83.

River shear zone of Christie (1990a). In this paper, this zone will be referred to as the Gilmour shear zone. The alteration zone identified in this study lying west of the Moira River is probably part of this system, likely offset to the south by a younger structure along the Moira River. It should be noted that the Gilmour shear zone is anastomosing, and may contain several splays. The second, younger structure along the Moira River is north- to north-northwest-trending, and likely extends from the south end of Wadsworth Lake to south of Queensborough. In this paper, this structure will be referred to as the Moira River fault. Locally, the Moira River fault forms the Belmont–Grimsthorpe domain boundary in the southern part of the map area. The fault has locally mylonitized rocks of both the Belmont and Grimsthorpe domains. From roughly 4 to 11 km north of Wolf Lake, the Moira River fault deforms rocks of the Gilmour and associated shear zones, resulting in further deformation and the introduction of late semi-concordant to discordant quartz veins. It may be no coincidence that most of the major gold prospects found to date occur where the Gilmour shear zone and the Moira River fault intersect.

Domain Boundary

Understanding the character of the Belmont–Grimsthorpe domain boundary is important, as it places key relative and absolute age constraints on the timing of alteration and gold mineralization within Grimsthorpe domain. Consequently, the domain boundary was examined in some detail.

The northern boundary is a 1 to 2 km wide upper greenschist to amphibolite facies zone of ductile deformation in dominantly mafic metavolcanic rocks, that are characterized by moderate to high magnetic susceptibility. This zone of increased magnetic character is reflected on the regional aeromagnetic surveys as an intense, linear magnetic high (Wadsworth anomaly of Abraham 1951). Rusty schist and sulphide-bearing quartzofeldspathic rocks are locally present along the boundary, particularly in the area between Gilmour and Gunter. Structure within the metavolcanic rocks parallels the contact. These deformed mafic metavolcanic rocks and gossanous rocks are in sharp contact with low-grade, grey, fine-grained carbonate rocks that preserve bedding and which locally contain well-preserved, primary, breccia and conglomerate beds. The carbonate rocks were likely deposited in a platform-slope environment (ramp-facies). Structural trends in the marbles show a variety of orientations near the contact. Layering in marbles within 50 m of the northern contact parallel the contact, and might represent mylonitic layering rather than bedding. This is an insignificant width, however, in comparison to the much broader and intense state of deformation observed in the metavolcanic rocks. Where intruded by plutonic rocks, the marbles are whiter in colour, and exhibit coarser grain size.

The southern domain boundary, between Highway 62 and the Moira River, is similar to the extent that carbonate-altered basalts are in sharp contact with low-grade, grey, fine-grained ramp-facies carbonate rocks, that preserve bedding. Siliciclastic beds are more common in the marbles in this area than to the north, as are secondary discordant dolomite veins. Structure within the marbles shows no direct relationship to the contact. Structure in the metavolcanic rocks along the southern contact do not parallel the contact, but for the most part, strike into the contact at high angle. Major alteration and deformation zones within the metavolcanic rocks cannot be traced into the marble sequence, suggesting that they formed earlier, and that the contact is likely faulted.

At the Moira River, the boundary becomes north-northwest-trending, and is characterized by a 300 to 500 m wide mylonite zone associated with the Moira River fault that affects both the marbles and the metavolcanic rocks. Small lozenges of marble mapped by Lumbers (1969) within the metavolcanic sequence within 250 m of the contact likely represent pods incorporated into the mylonite zone. Continuing southward to the Wolf Lake area, the contact is not well exposed, but is likely mylonitic.

The western contact in the Jordan and Glanmire Lake area is not well exposed, but is cut by gabbroic and granodioritic rocks, most notably the Tudor gabbro.

As illustrated in Figure 14.3, the domain boundary is folded. This folding appears to be pre-emplacement of the Tudor gabbro. The Tudor gabbro itself has not been dated, but has been assigned on the basis of chemistry to the Lavant intrusive suite (circa 1245 Ma; Easton 1992).

Is the Grimsthorpe domain thrust onto Belmont domain, or vice-versa? Gravity modelling by Real and Thomas (1987) indicates depth extents of 3 to 5 km for rocks across the entire Grimsthorpe domain, suggesting that it does not represent a thin thrust sheet. Modification of an unconformable contact cannot be ruled out, nor can a combination of steep-dipping fault contacts. The observations noted above clearly indicate that at least 3 types of structural contact are present, 2 of which have likely been folded, suggesting a complicated history of boundary formation.

Tectonic History of Western Grimsthorpe Domain

Significant events in the tectonic evolution of western Grimsthorpe domain, and their relative and absolute timing are as follows:

- Eruption of Canniff Complex mafic metavolcanic rocks and emplacement of mafic and ultramafic plutons of the Canniff Complex. Subsequent deformation and metamorphism up to amphibolite facies.
- Deposition of mafic metavolcanic rocks and mafic volcaniclastic rocks of the Grimsthorpe Group, locally, deposition of black shales and minor dolomite marbles, perhaps of exhalative origin. This occurs prior to, or at 1279 Ma, the age of felsites within the Tudor Formation.
- Development of deformation and alteration zones of the Gilmour shear zone and emplacement of early quartz veins. This might be associated with folding of the Grimsthorpe Group–Canniff Complex contact. More than one phase of alteration and deformation may have occurred.
  Gold mineralizing event.
- Emplacement of Lingham Lake intrusive complex, which also results in mafic and felsic diking in the metavolcanic sequence. Lingham Lake intrusive complex cuts altered rocks of the Gilmour shear zone.
- Emplacement of tonalite and granodiorite plutons of the Elzevir intrusive suite (circa 1270 Ma).
- Formation of Belmont–Grimsthorpe domain boundary and subsequent folding of this boundary.
- Emplacement of the Tudor gabbro (circa 1240 Ma).
- Formation of the Moira River fault and subsequent modification of the Belmont–Grimsthorpe domain boundary. Additional deformation and quartz veining within Grimsthorpe domain supracrustal and plutonic rocks.
  Gold mineralizing and/or remobilization event.
- Emplacement of syenite plutons in both domains (circa 1085 Ma), roughly synchronous with regional greenschist-facies metamorphism in Belmont domain.
  Localized gold mineralizing and/or remobilzation event.

Development of the gold alteration zones appears to have occurred prior to juxtaposition of the Belmont and Grimsthorpe domains, and there is no indication that the abundance of carbonate alteration in western Grimsthorpe domain is related to proximity to the carbonate-rich Belmont domain. In order to further constrain the absolute timing of gold mineralization in western Grimsthorpe domain, geochronology samples were collected from a non-mineralized felsite from the Main Prospect of the Chard–Dillman property, and from a phase of the Lingham Lake intrusive complex that cuts altered metavolcanic rocks of the Gilmour shear zone.

Geophysics and Geochemistry

MAGNETICS

Magnetic susceptibility readings from most mafic metavolcanic and metamorphosed volcaniclastic rocks within central Grimsthorpe domain were remarkably uniform, and showed no meaningful variation among stratigraphic unit at the micro or the macro scale, with average readings of 0.50 to 0.90 (Table 14.1). These even included measurements taken from outcrops of well-preserved, representative, units mapped by Easton and Ford (1994). These readings are lower than might be expected for a volcanic sequence thought to be subjected to only lower greenschist-facies metamorphism; but they are typical of readings from rocks found in parts of the Grenville Province subjected to high-grade metamorphism (Easton, unpublished data, 2002, 2003). One explanation for the low readings is that the supracrustal rocks in Grimsthorpe domain were subjected to more than one metamorphic event, with the earlier event being sufficiently intense to destroy the remnant magnetic character of the rocks.

The notable exception to this low magnetic character occurs within a 1 to 2 km wide zone located along the northern boundary of Grimsthorpe domain, where deformed metavolcanic rocks have magnetic susceptibility readings ranging from 10 to 90. This zone also corresponds to a prominent linear magnetic high observed on the regional aeromagnetic total field and first vertical derivative maps (Gupta 1991a, 1991b). It is likely that the high-magnetic character of these rocks reflects processes related to domain boundary formation, and is not a primary volcanic signature.

Older intrusive rock suites within Grimsthorpe domain, including the Grimsthorpe, Weslemkoon and Elzevir tonalite plutons (circa 1270 Ma), the Killer Creek gabbro suite (>1270 Ma), and gabbro bodies within the volcanic sequence (units 2 and 5 of Easton and Ford 1994, >1270 Ma) also have low magnetic susceptibility (0.15 to 0.70). This is reflected in the magnetically quiet zone that characterizes Grimsthorpe domain on the regional aeromagnetic total field and first vertical derivative maps (Gupta 1991a, 1991b).

In contrast, the Tudor gabbro (circa 1245 Ma), which appears to have intruded across the Belmont-Grimsthorpe domain, is characterized by high magnetic susceptibility, particularly along its northern margin (average readings of 60 to 120). The syenitic Gawley Creek, Mount Moriah and Skootamatta plutons (circa 1085 Ma), which also occur in both Belmont and Grimsthorpe domains are also characterized by moderate magnetic susceptibility (average readings of 20 to 40). This suggests that regional metamorphism after 1245 Ma was not of sufficient intensity to destroy the magnetic character of these younger plutonic rocks, and suggests that the low magnetic character of most rocks in Grimsthorpe domain was acquired prior to 1245 Ma.

RADIOMETRICS

The map area is covered by a high-resolution, airborne, gamma-ray spectrometric survey (Carson et al. 2004a-f). Most of the area of western Grimsthorpe domain is characterized by low values for potassium, uranium and thorium, except for areas underlain by rocks of the Elzevir suite, which have moderate potassium and uranium values, and the Mount Moriah syenite, which is characterized by high potassium, uranium and thorium contents.

High-resolution airborne gamma-ray spectrometric surveys have proven useful in delineating regional alteration patterns in some mineral camps (e.g., Ford 1982), and this method may be applicable to the study area. Topography, glacial cover and outcrop exposure are relatively uniform over most of the study area, and, for example, in the case of the Elzevir suite plutons, there is a close correspondence between mapped geological contacts and gamma-ray signature. These observations suggest that the

Table 14.2. Summary of gamma-ray anomalies present in supracrustal rocks in western Grimsthorpe domain. UTM co-ordinates approximate the centre of the anomalies.

Location	Easting Zone 18	Northing NAD 83	Anomalies	Comment
Moira River South	297000	4958000	U high, U/K high, U/Th high	Underlain by area of ankerite-rich altered basalts, Hodgson Au occurrence
Northern Wolf Lake	299500	4953000	Th/K high	No known occurrences, southward extension of alteration zone?
Mono gold	298000	4947000	U/K high, moderate U/Th	Advanced prospect
Moira River North	297000	4965000	Th/K, U/Th, U, U/K highs	Near Vardy Au prospect
Gilmour	299000	4969000	Th/K, U/Th, U, U/K highs	North of Gilmour mine, in area of Homestake Au showings
Tudor west	294500	4963000	Th/K, U/Th, U/K highs	No known occurrences
Black River	304800	4967000	Moderate U/Th	Black River Au prospect

observed gamma-ray anomalies in Grimsthorpe domain reflect either a bedrock signature, whether it be directly through outcrop exposure or in soils developed above bedrock anomalies.

Table 14.2 lists several moderately anomalous areas within the supracrustal rocks present in the study area. Most of the anomalies are observed on the elemental ratio maps, likely because they better resolve small local differences. In most cases, thorium (Th) is the element chiefly responsible for the anomalies listed in Table 14.2. The Moira River South, Moira River North, Gilmour, Black River and Mono Gold anomalies are all associated with highly carbonatized, silicified, and variably mineralized alteration zones. Potassic alteration in these zones is manifested by the development of biotite-rich (over 15% biotite). The northern Wolf Lake anomaly is not associated with known mineralization, but it does lie along the trace of the alteration zone that underlies both the Hodgson and Quarry occurrences. The Tudor west anomaly is in an area of poor exposure, but moderately carbonatized metabasalts occur north and south of this anomaly, near a north-trending felsite body. Both the areas underlain by the northern Wolf Lake and Tudor west anomalies may warrant additional exploration.

LAKE SEDIMENT GEOCHEMISTRY

The map area is covered by a lake sediment geochemical survey (Geological Survey of Canada–Ontario Geological Survey 1977). Most of the stations within the study area showed no responses for elements such as As, Co, Cu, Ni, Pb and Zn; unfortunately, Au was not analyzed. A sample collected southwest of the Gilmour mine at 298714E 4966226N, Zone 18, NAD 83, was anomalous for Cu, Pb and Zn (67, 44 and 79 ppm, respectively). Similarly, a sample south of the Gilmour mine at 300663E, 4966023N, Zone 18, NAD 83, was also anomalous for Cu, Pb and Zn (46, 34 and 82 ppm, respectively). Waters from the Gilmour mine area do not drain into either sampled pond, thus, the anomalies may be locally sourced, possibly from rusty schist horizons. Copper was also anomalous (75 ppm) in a sample collected at 297732E, 4961631N, Zone 18, NAD 83. This sample was collected from a pond east of the Moira River, roughly 400 m east-southeast of the south extension of the Chard–Dillman property in Tudor Township, and on strike with the major alteration zone that underlies the Hodgson occurrence to the south. A pond east of the Jordan River, near the marble–metavolcanic contact at 295497E, 4958122N, Zone 18, NAD 83 was extremely high in arsenic (17 ppm). This pond is at the southern terminus of a major carbonate alteration zone, and the author collected several arsenopyrite-rich rocks for assay roughly 500 m west of the pond. Wolf Lake was also anomalous for Cu, Pb, Zn and As (49, 22, 94,and 5.5 ppm, respectively).

Discussion

CONTROLS ON GOLD MINERALIZATION

Several factors play a role in gold mineralization within the map area, as discussed below.

Location of Gold in Sheared and Altered Rocks

Within altered mafic metavolcanic rocks of the Gilmour shear zone, Christie (1990a) noted that gold mineralization was found in 1) foliation oblique quartz veins, or in 2) disseminated to stringer sulphide mineralization in strongly sheared and iron-carbonatized altered rocks. Dillman (1997) noted that sheared ankerite-rich rock can average 0.7 g/t Au and that carbonated rock with pyrite can return assays of 1.6 g/t Au. Sugary quartz veins with associated arsenopyrite and pyrite can assay 1 to 5.6 g/t Au. In the altered felsites, chloritized felsite with lensoid quartz and arsenopyrite assay 0.5 to 1 g/t Au, whereas mylonitized felsite with disseminated arsenopyrite can average 5.7 to 8.4 g/t Au (Dillman 1997).

Stratigraphic Controls

Shearing and alteration may be localized near the Canniff Complex–Grimsthopre Group contact. The Black River, Hodgson, and Homestake occurrences all occur at or near this contact. This contact may have simply focussed fluid flow, rather than reflecting any direct host rock control.

The felsite body underlying the Chard–Dillman property in Tudor Township is significantly enriched in gold (*see* Table 14.1), however, there are no other reports from the map area of similarly mineralized felsites. This property is located at the intersection of the Gilmour shear zone and its splays and the Moira River fault; consequently, structural control of mineralization may be the overriding factor at this site.

Rusty schists occur throughout the study area, and are common within the Gilmour shear zone, but despite their sulphide content, do not seem to be systematically enriched in gold or base metals. The Tulonen–King occurrence is an exception to this statement, however, it is located along the western edge of the Moira River fault, and may include sheared and altered rocks of both the Belmont and Grimsthorpe domains. Thus, it may not be representative of the Grimsthorpe domain rusty schist zones.

Gold Models

The alteration systems observed in the mafic supracrustal rocks of western Grimsthorpe domain have many similarities to Archean lode-gold systems (e.g., Colvine et al. 1988). Especially with respect to the dominance and intensity of carbonate alteration. The variety and timing of quartz vein systems, and the association of gold with zones of sulphidation, potassic alteration and oxidation. If this analogy is meaningful, then the Gilmour shear zone exhibits many characteristics of the brittle-ductile transition, whereas ductile deformation features appear to dominate along the Moira River fault.

Other Types of Gold Mineralization

UNCONFORMITY-RELATED GOLD MINERALIZATION

The author located an area of carbonate and hematite alteration in leucogabbro of the Lingham Lake intrusive complex, at 298775E, 4956400N, Zone 18, NAD 83, adjacent to an exposure of red, hematite-rich weathering crust. Similar alteration and weathering crusts are locally associated with gold mineralization along the Paleozoic unconformity in the Madoc area (Di Prisco and Springer 1991), and some of the reported gold mineralization from the Lingham Lake intrusive complex may be related to similar weathered zones. A lead lake sediment anomaly within the Lingham Lake intrusive complex is reported to be hosted in Paleozoic limestone (Geological Survey of Canada–Ontario Geological Survey 1977) and may represent another example of unconformity-related mineralization.

SYENITE-RELATED GOLD MINERALIZATION

The host rocks to the Mono gold prospect, namely rusty schists and mildly altered mafic metavolcanic and metagabboic rocks, are similar to those seen elsewhere in Grimsthorpe domain. Unlike other Grimsthorpe domain occurrences, however, the gold-bearing quartz and quartz-carbonate veins lie at a high angle to the lithological contacts and are not clearly related to any regional structure (LeBaron 1991, p.90-98). In addition, although the veins trend at 345° to 360°, they dip shallowly (40° to 45°) to the east (LeBaron 1991). Gold is found in association with telluride minerals and bismuth, and it has been suggested that mineralization is associated with a syenite intrusion at depth (LeBaron 1991). The Gawley Creek syenite is exposed only a few hundred metres west of the Mono gold prospect, and the former Bannockburn gold mine, located west of Highway 62, is hosted in rusty schist at the contact of the Gawley Creek syenite (Malczak, Carter and Springer 1985). It is possible that the gold mineralization seen at the Mono gold prospect is the result of remobilization caused by hydrothermal fluids circulating around the margin of the Gawley Creek syenite.

RECOMMENDATIONS FOR EXPLORATION

Gold-Copper-Arsenic

The intersection of the Gilmour shear zone with the Moira River fault is a prime exploration target. The area roughly 10 km north of Wolf Lake near the powerline has been extensively explored, but the area along the Moira River from roughly 6 km north of Wolf Lake to Wolf Lake has not been extensively explored.

The area surrounding the lake sediment anomaly for arsenic, near the marble–metavolcanic contact east of the Jordan River, lies at the southern end of a long, linear belt of schistose and highly carbonatized metavolcanic rocks, and the area around this pond warrants further examination. The aforementioned linear belt of schistose and highly carbonatized metavolcanic rocks of the Gilmour shear zone, located east of Pine View Ridge road and the Moira River has been previously under explored, but is currently well exposed due to logging. The Tudor west and Wolf Lake north gamma-ray anomalies also warrant further examination, especially the Tudor west anomaly, which is associated with a felsite unit.

Ironically, many of the exploration trenches dug by Lydia Diamond Exploration of Canada Limited, east and northeast of Wolf Lake, expose schistose, carbonatized, and veined metabasaltic rocks, with the most intense alteration and veining being present in the vicinity of the quarry on the Wolf Lake access road. The metavolcanic belt east and northeast of Wolf Lake is a promising exploration target if this ground becomes available for staking in the near future.

Exploration techniques for gold that have proven successful in the area include soil geochemical surveys (Christie 1990a) and heavy mineral sampling of stream gravels (Dillman 2003a). Heavy mineral sampling of tills has not been successful in identifying gold exploration targets (Dillman 2003a).

At present, it is not known if there is any connection between the degree of secondary magnetite formation in the alteration zones and the grade of gold mineralization in the altered rocks. Hodgson (2000) did report significant gold results from soils sampled over one of 5 magnetic anomalies present on his claims. Currently, the utility of either ground magnetometer surveys or magnetic susceptibility measurements of exposed rocks as an exploration tool cannot be evaluated.

As previously mentioned, only low-grade gold and arsenopyrite mineralization has been reported from vein systems located within the Lingham Lake intrusive complex (e.g., Lumbers 1969, *see* also Table 14.1). If the combination of carbonate alteration within the Gilmour shear zone and subsequent deformation and quartz veining along the Moira River fault is needed to produce significant gold enrichment, then the Lingham Lake intrusive complex is not a prime exploration target for gold.

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15. Project Unit 00-101. Summary of Geophysical Projects and Activities

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INTRODUCTION

The focus of efforts this year has been the support of the bedrock mapping program through the integration of geology and geophysics. Increased emphasis has been placed on collaborative interpretation of geoscience data. The acquisition of 3-D inversion potential field modelling software and the increased use of fast 2-D magnetic modelling tools has resulted in improved interpretations of the subsurface. The publication of data sets, from surveys commissioned by Discover Abitibi and the Lake Nipigon Region Geoscience Initiative (LNRGI) has resulted in a significant increase in geophysical data publicly available in Ontario. In addition, client support and training activities have continued throughout the year.

Geophysical projects and activities for 2004 covered the following areas

1. Support for the bedrock mapping program
2. Data acquisition
3. Data distribution
4. Regional geoscience initiatives
5. Training and education
6. Other activities

SUPPORT FOR THE BEDROCK MAPPING PROGRAM

Geophysical support for bedrock mapping projects continued for the Precambrian Geoscience Section and the Sedimentary Geoscience Section of the Ontario Geological Survey (OGS) as part of a strategy to enhance the value of products through field mapping, interpretation and modelling. Mapping projects now routinely utilize magnetic, electromagnetic, gravity and resistivity and/or conductivity data plus corresponding derivatives. Assistance is provided to field geologists through preparation of digital images and hard-copy maps using a variety of display techniques. Integrating geophysics into mapping projects has been facilitated by the use of geographic information system (GIS) software and by the availability of high-quality airborne geophysical survey data that have been acquired in recent years.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.15-1 to 15-5.

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As part of the continuing effort to use regional geophysical and other data sets to the greatest benefit of the geological mapping program, a new collaborative interpretation approach was used on two of the projects (Opikeigen Lake and west-central Nipigon Embayment) prior to the start of the field season. The outcome of these exercises was the development of preliminary interpretation maps and identification of priority areas for mapping. L.A.F. Hall (this volume) describes the procedure in greater detail.

Modelling of magnetic data has been facilitated by the use of magnetic susceptibility data now routinely collected as part of the bedrock mapping program. University of British Columbia 3-D smooth model inversion software and other simpler and faster modelling tools have been used to provide insight into specific mapping problems. The magnetic susceptibility data will be incorporated into a geological database presently being developed for Precambrian projects (Madon, this volume).

Geophysical support was provided for the following projects during 2004:

- Abitibi greenstone architecture project (Discover Abitibi)
- Abitibi greenstone belt compilation (project 95-024)
- Bannockburn area (project 04-021)
- Carmen–Langmuir townships (project 00-011)
- Grimsthorpe area (project 04-013)
- Hudson Bay–James Bay Lowlands Archean Substrate (projects 98-006 and 98-007)
- Lac des Mille Lacs area (project 95-014)
- Menzies–Musquash townships (project 03-002)
- Opikeigen Lake area (project 04-006)
- Porter–Vernon townships (project 04-016)
- Temagami area (project 99-315)
- West-central Nipigon Embayment (project 03-304)
- Western Nipigon Embayment (project 03-001)

DATA ACQUISITION

In 2003, the Ontario Geological Survey acquired, from Aur Resources Inc., legacy airborne magnetic data and electromagnetic data for 8 surveys within the southern part of the James Bay lowlands, north and northeast of Hearst (Figure 15.1). The surveys, which have been grouped into 3 areas, namely Squirrel River (S1, S2, S3), Otter Rapids (O1, O2, O3, O4), and Moose River (M1), have been digitally reprocessed and prepared for publication. They are currently withheld from release under a confidentiality agreement and will be published on the first scheduled release date after July 2005.

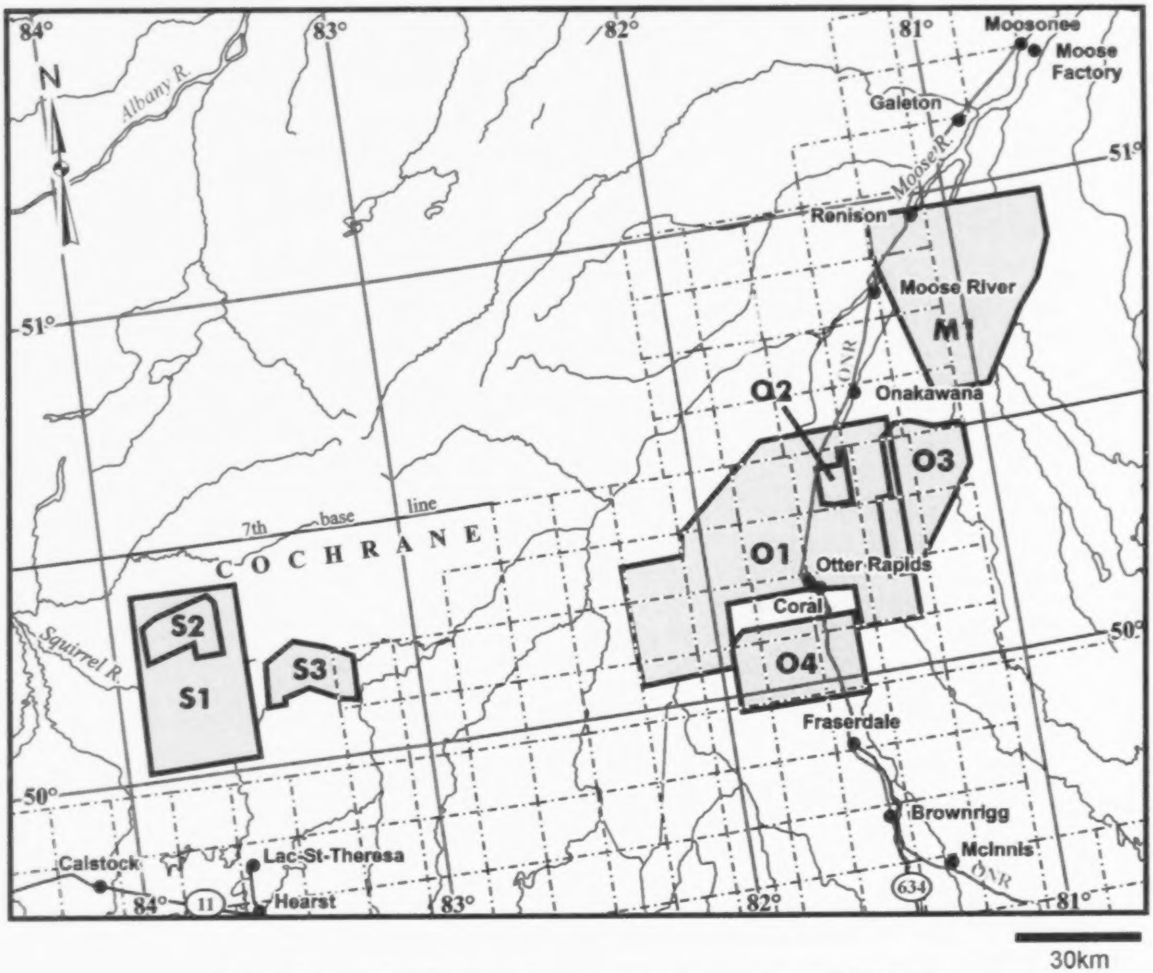
84°
83°
82°
81°
Moosonee
Moose Factory
N
Albany R.
Galeton
Moose R.
51°
Renison
Moose River
M1
51°
ONR
O2
Onakawana
O3
7th
base
line
C O C H R A N E
O1
Otter Rapids
Coral
S2
Squirrel R.
S3
S1
O4
50°
Fraserdale
50°
Brownrigg
McInnis
ONR
Calstock
Lac-St-Theresa
84°
11
Hearst
83°
82°
634
81°
30km

Figure 15.1. Location of legacy airborne surveys in the James Bay Lowlands area.

DATA DISTRIBUTION

Airborne geophysical survey data were released, via the OGS, in 10 publications during 2004. With the exception of the Shaw Dome area survey, all data were newly acquired. The total line-kilometres for the surveys published in 2004, to date, was 129 220 kilometres. Table 15.1 summarizes the information for these geophysical data sets (GDS).

In order to assess new data distribution technology, a Data Access Protocol (DAP) internet site, similar to that currently being used by the Geological Survey of Canada, was set up for the Ministry of Northern Development and Mines (MNDM) by Geosoft Inc. on a test basis. The site was found to work successfully for the duration of the internal test. Wider in scope, the MNDM has launched the Geoscience Data Portal project to develop and maintain an internet portal for the discovery and free electronic transfer of Ontario's digital geoscience information. Ontario geophysical data sets may be obtained from the MNDM Publication Sales department (tel. 1-888-415-9845; email: pubsales@ndm.gov.on.ca).

Table 15.1. Releases of airborne geophysical survey data in 2004.

Survey Name	**Publication No.**	**Release Date**	**Survey For**	**Survey By**	**Survey Type**	**Line-Kilometres [Stations]**
Reid–Mahaffy Test Area	GDS 1045	April	Discover Abitibi	Fugro	Airborne Magnetic, Electromagnetic MEGATEM	n/a
Shaw Dome Area	GDS 1046	April	Discover Abitibi	Outokumpu	Airborne Magnetic, Electromagnetic (FDEM)	3111
Lake Nipigon Embayment Area	GDS 1047	April	Lake Nipigon Region Geoscience Initiative	Fugro	Airborne Magnetic, Gamma-Ray Spectrometric	49 671
Round Lake Batholith Area	GDS 1048	May	Discover Abitibi	Fugro	Airborne Magnetic	21 310
Central Abitibi Destor–Porcupine–Pipestone Faults Area	GDS 1049	August	Discover Abitibi	Fugro	Airborne Magnetic	16 088
Lake Abitibi Area	GDS 1050	September	Discover Abitibi	Fugro	Airborne Magnetic	11 715
NE, NW and South Timmins Areas	GDS 1051	TBA	Discover Abitibi	Sander Geophysics	Airborne Gravity	14 296
Lake Nipigon Embayment Area	GDS 1052	September	Lake Nipigon Region Geoscience Initiative	Abitibi Geophysics	Ground Gravity	[4091]
Kirkland Lake–Larder Lake	GDS 1053	TBA	Discover Abitibi	Fugro	Airborne Magnetic	13 029
Reid–Mahaffy Test Area	GDS 1111	June	Operation Treasure Hunt / Discover Abitibi	Fugro	Airborne Magnetic, Electromagnetic: GEOTEM, MEGATEM	n/a

REGIONAL GEOSCIENCE INITIATIVES

Continuing support has been provided to the Discover Abitibi and the Lake Nipigon Region Geoscience Initiative government–industry collaborative projects. Assistance included the provision of geophysical maps and images to geological mapping crews, interpretation and modelling of some data sets, as well as aid in the publication of geophysical data sets.

A total of 7 data sets were released for Discover Abitibi (*see* Table 15.1). Included in this number is the Shaw Dome survey reprocessed from data supplied by Outokumpu Mines Ltd. and 2 releases over the Reid–Mahaffy airborne test site, supplementing previously released test data (MRD 55). Geophysical maps and images were prepared, for field use, in order to assist geologists working on the Abitibi greenstone architecture project.

Magnetic and gamma-ray spectrometer data, collected last year during the airborne geophysical survey for the Lake Nipigon Region Geoscience Initiative, were used to help refine geological contacts in areas of poor bedrock exposure in the mapping areas of 2003. Also, through a collaborative interpretation exercise, the airborne geophysical data were used to create an interpretative map prior to the start of bedrock mapping in 2004. The results of a 4091-station gravity survey, covering the western and southern margins of Lake Nipigon, were released in September 2004. The data, in conjunction with the airborne magnetics and physical property measurements, are being modelled using 3-D inversion software in order to obtain insights into the structure of parts of the Nipigon Embayment at depth. As part of an OMET funded project, being carried out by MIRARCO, the 3-D inversion modelling is being integrated with other geoscience data using GOCAD software for visualization in their virtual reality laboratory at the Willet Green Miller Centre in Sudbury.

TRAINING AND EDUCATION

A half-day course, covering the interpretation of airborne electromagnetic and magnetic surveys, was developed for delivery at the Northwest Ontario Mines and Minerals Symposium in Thunder Bay. The objective of the course was to provide prospectors and non-specialists with the understanding to make basic interpretations of airborne geophysical maps for mineral exploration purposes. The course comprised practical exercises and oral presentations. Also, a presentation on the use of regional geophysics for mapping was delivered to graduate students at Laurentian University.

OTHER ACTIVITIES

The web-based Geophysical Atlas, which shows the disposition of public domain geophysical data in Ontario, has been extensively updated. New data releases have been added to the site, the layout and graphics have been improved and links to Land Information Ontario (LIO) metadata have been added. The latter enhancement provides much more information on survey parameters than was previously the case. The Geophysical Atlas is found on the MNDM web site at : http://www.mndm.gov.on.ca/mndm/mines/ogs/gpxatlas/default_e.asp

Client support continues to be a significant activity. The bulk of support for external clients involves requests for geophysical information, enquiries about the use of geophysical data and questions regarding the availability of data.

16. Project Unit 02-031. From Duksbak™ to iPAQ™: Developing a Digital Data Collection System for Bedrock Geology Field Mapping

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INTRODUCTION

The goal of this project is to develop a more efficient and streamlined process for digitally collecting field observations that integrates with geographic information system (GIS) for geological map production. The 3 project objectives are to determine the best software and hardware for digital data collection in the field, establish a new system of data collection and flow from field to office for GIS map production and data storage, and to increase the amount of data available to a geologist on handheld units in order to make more informed field observations. Adopting a GIS-friendly field data collection system will bring the entire bedrock mapping process into the GIS world, but developing a system that works for all field mappers is challenging. Developing a new system that geologists will be comfortable using requires more than choosing new software and hardware. A more holistic approach integrates corporate mapping policies, and assesses staff needs before selecting software and hardware.

PROJECT DESIGN

A two-year methods development project was initiated in 2003 to develop a new field mapping system. This project builds on past work by revitalizing digital field data collection with handheld computers, and developing a system that integrates with GIS. A common approach for developing new information management systems was adopted for this project (Consultative Group to Assist the Poor (CGAP) 2003). The project team is guided through 6 core phases, from planning to system management. This project focusses on the initial phases of planning, needs analysis, design and selection. Implementing and managing the new system will follow in subsequent years. The 6 core phases of developing a new system are

- **Project preparation** – build the project team; define goals, performance measures
- **Needs analysis** – identify and summarize needs of users, technical needs
- **Design** – quantify requirements
- **Selection** – research possibilities, field test, discuss with other groups
- **Implementation** – develop manuals, train geologists, field use
- **Management** – ongoing support, problem solving, optimizing

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Summary of Field Work and Other Activities 2004,
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PROJECT PREPARATION

Team Building

Developing a new system for field data collection that will be accepted by Precambrian Geoscience Section (PGS) geologists requires their direct input. While all PGS staff will be involved in the needs analysis, it was critical to have geologists directly involved throughout the process. The best way to have direct involvement is to incorporate a mapping crew into the project. Geologists working on the Lake Nipigon bedrock mapping project were chosen to spearhead field testing because of the core geologist's extensive background with digital data capture, technology knowledge, and the fact the all geoscience data generated by the project will be compile into a final GIS product. The project team includes an applicationist, 2 field geologists, field support staff, and management.

Defining Goals

The main goals of this project are to develop a process to integrate field data into the GIS environment, select appropriate data collection software, assess new hardware, and test the efficacy of real-time data entry. The process must balance the needs of geologists for flexible data entry, yet have a relevant level of data structure standardization.

Performance Measures

Performance measures quantify the success of the project, and provide specific targets to work toward. The new system must be at least as efficient and as fast as current systems and reduce time spent by support staff migrating mapping data to the GIS environment. Using handheld computers (i.e., personal digital assistants (PDAs)) for real-time data collection should reduce time spent entering data later by removing duplication of effort. Although hard to quantify, the increased analytical capabilities geologists achieve by adopting GIS should be taken into consideration when assessing additional time required for entering data.

NEEDS ANALYSIS

A central goal of this project is to incorporate user needs, corporate needs, and technical needs into the data collection system (Teaching and Education Institute 2003). Most geologists are happy with the current data collection software content and design, and hope to see many of its components reflected in the new system. Corporate needs include standardized maps and adoption of GIS technology. Technical needs include aspects such as hardware design. Initial focus was on finding a solution that met the basic corporate needs, as well as the needs specific to the field testing geologists. These needs have been compiled into an initial user needs survey that will be distributed to all PGS staff following the second field season. Feedback received from the geologists will be assessed, rated, and then incorporated into the final user needs analysis document.

Data collection needs of PGS geologists are very diverse and extensive, but a few key needs are universal to all users. Key needs include software that supports a relational database structure (1 station and many lithologies), integration with our GIS software, be form-based, collect spatial x–y data, be very easy to use and very easy to customize, be secure and stable. The user needs analysis document is divided into 2 main groups:

Hardware

- physical features (portability, ruggedness, speed)
- interoperability (operating system, compatibility)
- peripherals (cables, expansion packs, optional hardware)

Software

- design (basic software construction)
- efficiency (speed, accuracy)
- company reputation
- software integration (with GIS, between operating systems)
- database architecture (storage, format)
- import and export
- back up
- forms and form design (functionality, data entry features, controls)
- ease of use (during data collection)
- data viewing (methods of looking at data)
- data editing (options, efficiencies)

DESIGN AND SELECTION

Designing a field data collection system brings together all the evaluation and analysis taken place so far. It outlines the system requirements based on priorities pulled from the user needs document. The system design is essentially a blueprint. The selection process includes finding a software and hardware solution that best fits with the design. Selecting software and hardware includes researching possibilities, talking with colleagues, and field testing (Hernandez 1997).

Systems are normally designed in isolation of the selection process, essentially without influence from software. We are actually working through the design and selection process simultaneously. Bringing these together has positively influenced the data collection system design. Simultaneous design and testing provides quick feedback, allowing us to solve problems as we progress, and spend less time designing a potentially flawed system. Exposure to other software designs removes residual biases that team members may carry over from their current system.

Successfully designing a GIS digital data collection system requires co-operation from team members, PGS geologists, software developers, and fellow users. We are very fortunate to have field crews testing system designs throughout the project. The persistence of field geologists, and their willingness to test system limits are proving invaluable. Team geologists are testing out new PDAs, integration methods, and updated software over 2 field seasons.

RESULTS OF YEAR ONE

Our co-operative and dedicated team, with generous support from colleagues, published PGS's first digital GIS field-based bedrock geology maps during the first year of this project. This great accomplishment can be attributed to a number of factors: good hardware choices, using relevant software, well-designed data forms, discovering a system for data integration with GIS, and extensive field testing.

Purchasing Good Hardware

Previous attempts by the PGS to collect field data with PDAs have met with limited success. An explosion in the PDA market encouraged us to re-try this technology. We borrowed 2 different styles of 'portable' computers from colleagues at the Ministry of Natural Resources. Many of the 'seasoned' geologists liked the larger notebook style, finding it easier on their eyes. Others really liked the portability of the smaller PDA, even though the screen is smaller. Our team geologists decided to use the smaller PDA units. There is a huge variety of PDAs available on the market, but all fall under 3 main types: lower-end models (personal organizers), higher-end models (data entry, larger file storage, more options), and professional models (ruggedised, with geographic positioning system (GPS) software and keyboards built in). The professional models would be most appropriate for us, but the cost is prohibitive. We decided to purchase HP iPAQ™ Pocket PC 3950 higher-end units. The processor speed, availability of expansion packs, and windows CE operating system met our basic needs without an enormous investment.

Software Choices

Field data collection software can be grouped into 2 main categories – database-only software, and database–mapping software (our preference). While not all geologists are planning to use PDAs for field data collection, all data must be in a digital GIS-friendly format. Software must function on both PDAs and laptops. Two software packages stand out: FieldWorker software, from FieldWorker Products Limited, (http://www.fieldworker.com) and ESRI® ArcPad™ (http://www.esri.com/software/arcgis/arcpad/index.html). The capabilities of FieldWorker are already familiar to PGS, having been adopted for previous PDA testing projects. Initial scoping of the capabilities of ArcPad™ quickly proved that extensive development time would be required to meet our form needs, and to provide a relational database structure.

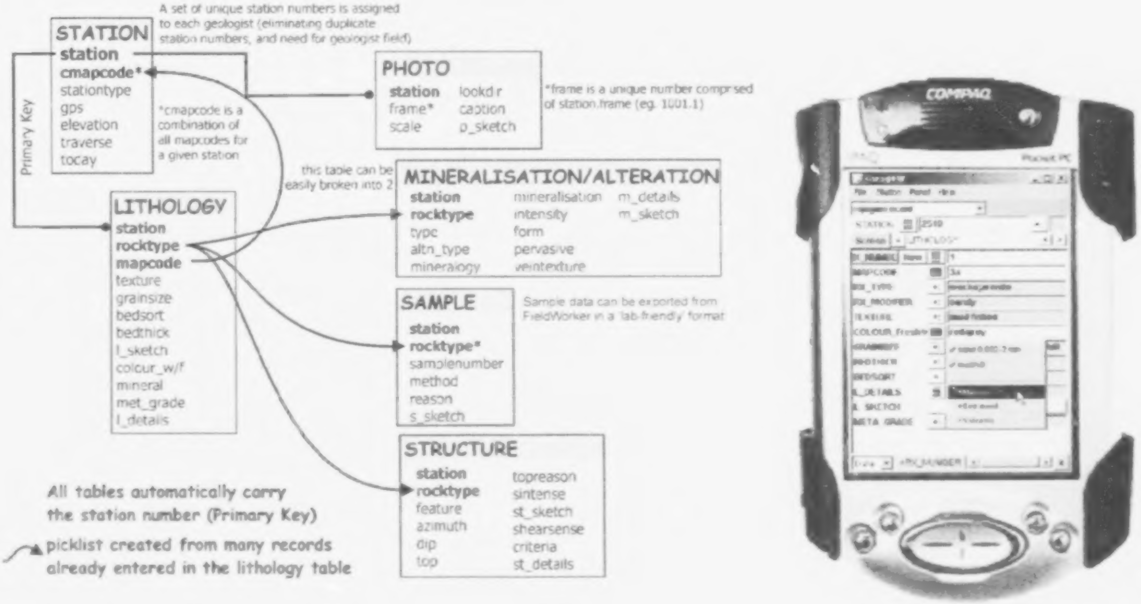
STATION
station
cmapcode*
stationtype
gps
elevation
traverse
tocay
A set of unique station numbers is assigned to each geologist (eliminating duplicate station numbers, and need for geologist field)
*cmapcode is a combination of all mapcodes for a given station
Primary Key
PHOTO
station
frame*
scale
lookdir
caption
p_sketch
*frame is a unique number comprised of station.frame (eg. 1001.1)
this table can be easily broken into 2
MINERALISATION/ALTERATION
station
rocktype
type
altn_type
mineralogy
mineralisation
intensity
form
pervasive
veintexture
m_details
m_sketch
LITHOLOGY
station
rocktype
mapcode
texture
grainsize
bedsort
bedthick
l_sketch
colour_w/f
mineral
met_grade
l_details
SAMPLE
station
rocktype*
samplenumber
method
reason
s_sketch
Sample data can be exported from FieldWorker in a 'lab-friendly' format
STRUCTURE
station
rocktype
feature
azimuth
dip
top
topreason
sintense
st_sketch
shearsense
criteria
st_details
All tables automatically carry the station number (Primary Key)
picklist created from many records already entered in the lithology table
COMPAQ
Pocket PC

Figure 16.1. Data model designed for project geologists. The iPAQ™ highlights the lithology form designed in FieldWorker.

In an effort to minimize time spent in the field learning new software systems, and the lack of programming knowledge, we decided to use FieldWorker for this project. Remaining with software already familiar to our geologists proved to be a wise decision. Many key needs defined in the user needs survey are met by FieldWorker. Past versions run on either PDAs or laptops, are form based, populate a relational database, and capture locations. FieldWorker also recently developed the functionality to integrate with GIS software.

FieldWorker ran well throughout the first field season for both field crews. Station locations were captured either via manual entry or directly from a connected GPS unit. The main concerns expressed by our geologists were that extensive pick lists slowed down the software, and that sending new form designs to the iPAQ™ was sometimes difficult.

Designing Forms

Forms are the essence of data capture systems. They reduce time spent entering data, provide a consistency for data entry, ensure that important data are collected, and minimize data entry errors. We have discovered that while many software packages allow form-based data collection, very few allow users to design forms that are robust enough to meet the needs of a field geologist. A large part of the first year of this project was spent assessing the form-design capabilities of various software packages. The importance of forms is clearly evident in the number of needs that have been included in the user needs survey. Researching various software applications during the first year of this project has shown that no other software can compete with FieldWorker's extensive and easy to use form design.

Field Testing

The 2 field crews were equipped with HP iPAQ™ hardware, FieldWorker and ESRI® ArcGIS® software. Our core geologist's past experience with FieldWorker software on an Apple® Newton® handheld computer was a real advantage. He designed the FieldWorker database forms, provided ongoing field support for the other crew, and was able to quickly assess, and often resolve minor problems. Keeping the process as simple as possible for the first field season paid off. Very few problems were encountered by either crew, and they successfully collected data for the entire season. Both geologists were able to make improvements to their data forms, and also to think about major form changes that could be implemented in the second field season.

Photo 16.1. Collecting data in the field using the HP iPAQ™ Pocket PC 3950.

Integrating Field Data into GIS

Data collected in the field must be integrated into our standard GIS software. While the focus of this project was initially to develop systems for bringing field data into GIS, a large part has developed into outlining how data can be used within the GIS. Geologists have not adopted GIS for mapping because of their dependence on computer-assisted drafting (CAD) for data entry and strong digitizing capabilities. Moving to GIS means that an entire new system has to be developed not only for data entry, but also for database design, and methods for constructing maps. We decided to keep this process as simple as possible for the first year, and then expand in the second year. Station data were exported from FieldWorker as "shapefiles" and all the 'many' data (lithologies, structures) were exported into database (*.dbf*) tables. These daily exports were then appended to the previous day's data. This system resulted in huge numbers of files being created, and the process of appending data was awkward. Software limitations meant that only the station shapefiles could be appended in ArcGIS®. All *.dbf* tables had to be appended using Microsoft® Excel and then re-imported into ArcGIS®.

ESRI® recently developed the geodatabase, a relational database structure for ArcGIS®. Prior to this, all ESRI® GIS data were stored in a series of flat files. This meant that the benefits of relational databases were lost as soon as data were imported into a GIS. Team members were excited about the possibility of carrying their field relational database structure into GIS. The geodatabase has not been widely used by PGS, and even gained a reputation as a 'mysterious' file format. Understanding geodatabases required extensive research, training, and many discussions with developers throughout the entire first field season. Geodatabases are primarily designed for higher end ArcGIS® licencing. Although many features are not available with ArcView® level licences, important features for data loading and basic database structure are functional. Adopting a geodatabase, even at the basic level, meant that geologists were able to maintain a relational database, and they gained a much more efficient system for importing field data.

A geodatabase was designed for the team that mirrored the FieldWorker database. All field data were then 'loaded' into the geodatabase using the new system. Both geologists were very happy with the streamlined data loading process, and noted significant time savings. Having all field data housed within a single relational database also greatly simplified GIS map construction. The team successfully published the first PGS fully digital GIS bedrock geology maps.

INTERIM RESULTS FROM YEAR TWO

The winter of 2003–2004 was spent adapting and improving the system design, and testing alternative software. Initial success with our basic system design meant that we were comfortable expanding, and building in many new features. Improvements were made to both FieldWorker and ArcGIS® systems. While we were all excited about the improved system, software changes by FieldWorker Products Limited threw a major kink into our plans. This resulted in major challenges throughout the first month of the field season. Working through these challenges, while frustrating, did push the limits of our project, and the outcome will be a more robust and secure system.

ArcGIS® Success

A great success from year one was implementing the geodatabase for map construction. The team enthusiastically switched from shapefiles to geodatabases for the project's second year. Spending design time up front is the key to implementing a geodatabase for field mapping. Time and effort spent in the spring of 2004 constructing a database that seamlessly merged with the FieldWorker database paid off. Both teams were able to successfully load all field data into the geodatabase throughout the entire mapping season.

Overcoming FieldWorker Challenges

We are very pleased with the level of support that we receive from FieldWorker Products Limited. They have customized software to better meet our needs, solved problems, and tested solutions using our own data. FieldWorker performed a major overhaul of their software over the past winter. This expanded software uses a server system, meaning that the PDA database synchronizes with a centralized computer database. This centralized computer manages all data, form design changes, and exports. This new design removes the ability of geologists to export data directly from the iPAQ™. The centralized server has not provided any marked benefit for us, and resulted in additional time required by team members to learning the new system, and ironing out software bugs.

The timing of the new software release was probably the biggest challenge of the second field season. While the new version was slated for release one month before the field season, it wasn't actually released until one week before our crews left for the field. We found major programming bugs with this new version, and didn't receive fixes until after the crews had left. Problems were again found during a trip to the field areas to set up the new software, field test, and fine-tune the data collection system. Discussions with FieldWorker Products Limited quickly solved our problems. Further challenges were encountered by one crew over the next few weeks, but they have been attributed to hardware problems.

In an effort to ameliorate further problems and time loss, both crews modified their field mapping systems. Our lead crew decided to revert back to a previous version of FieldWorker. The other crew, having more hardware issues than software, opted to stop using the iPAQ™, and instead installed the new version of FieldWorker on their laptops. Testing data entry with FieldWorker on a laptop proved beneficial, as many PGS geologists prefer to collect data in a notebook (or using Duksbak™ paper), and enter the data into the computer at night. Both crews overcame challenges in different ways, and were successful in getting their field data into the geodatabase.

In hindsight, we should not have pushed through the new software version for this field season. The problems encountered were numerous, and too much time was spent by geologists trying solve problems. Much of this could have been managed if we had received the software at least one month before the field season.

Alternative Software

The main alternative software that we are testing is ArcPad™. ArcPad™ is a direct extension to ArcGIS®. The seamless integration between ArcGIS® and ArcPad™ is a definite asset, as is the mapping capability of ArcPad™. Initial testing and research, however, quickly pointed out fundamental challenges with the software. ArcPad™ does not support a relational database structure, and form design is extremely rudimentary. Enhancing these functionalities is possible, but requires non-custom programming.

We developed a project proposal for testing customizing ArcPad™, and presented it to the Sault College GIS program leader as a possible co-operative education project. We housed a co-operative education student with extensive programming experience for a one-month placement. Our student did make progress by extending the form design functionality, and providing support for populating a semi-relational database. Equally important, however, we realized the complexity involved with customizing software.

FALL 2004: IMPLEMENTATION

After a rocky start to the 2004 field season, both geologists had success collecting field data for the rest of the summer. Although one crew gave up the iPAQ™, they were able to test the new laptop version of FieldWorker. Adopting geodatabases has made data integration much more efficient. We anticipate that the increase in mapping functionality and accessibility of field data will help geologists make better maps.

The user needs analysis will be completed by early fall 2004. All PGS staff will receive a copy of the initial survey to make comments and additions. The final user needs analysis will be used to 'grade' software options, and decide which software will be implemented. Once a software package is chosen, user manuals and final system designs can be created. Geologists can then be trained. We are anticipating that a new system will be in place for the 2005 field season.

Methods development projects are unique entities. They are normally linked to core type projects, and progress in partnership with them. One of the biggest challenges with methods development projects is balancing time between development work and the core project. This project did tip the scale on the development side during the second field season. This should be balanced during the fall, with less development time spent in ArcGIS® making maps. The dedication, co-operation and diversity of our team will be the key to developing a successful field data collection system while also producing 4 bedrock geology maps for the Lake Nipigon Region Geoscience Initiative.

ACKNOWLEDGMENTS

I would like to sincerely thank Tom Hart for his patience, persistence, constructive criticisms, and willingness to test new systems. Thanks also to Carole Anne MacDonald, Mariska terMeer and Enrick Tremblay for sticking with the project. Thanks to Jack Parker for providing me the opportunity to lead such an interesting and challenging project.

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17. Project Unit 04-019. Designing a Geological Data Model for the Next Generation of Digital Maps

Z.B. Madon[1]

[1]Precambrian Geoscience Section, Ontario Geological Survey

INTRODUCTION

To enhance Ontario's mineral sector competitiveness, the Precambrian Geoscience Section (PGS), of the Ontario Geological Survey, initiated a project to design and develop a "corporate" geological data model for the next generation of digital maps. Without restricting the creativity of our mapping geologists, this multi-year collaborative project will attempt to develop a comprehensive and robust data model to both streamline the acquisition, compilation and dissemination of geological information and to make PGS maps "interoperable"[2] and "scalable"[3].

WHY DO WE NEED A CORPORATE DATA MODEL?

PGS has almost 2 decades of experience in producing geological maps using computer technology. The *Computer Field Note System* (Stott and Ambrose 1985) allowed geologists to record spatial geological data that was then used to produce geological maps and stereonets. The *Fieldlog* program (Brodaric and Fyon 1989) evolved from this to let geologists store map-related information in a true relational database, process it and display it using AutoCAD® software. Fieldlog is still being used in the PGS, but is gradually being replaced by more powerful GIS systems (ArcGIS®).

To this day, PGS geology maps are designed and tailored by the project geologist to suit i) the area being mapped, ii) the unique geological problem being addressed or iii) the geologist's particular area of expertise. This approach gives the geologist maximum flexibility and creativity, but tends to create isolated silos of information (Figure 17.1). Each geological legend is a unique mix of lithologic, lithostratigraphic, stratigraphic, tectonic and genetic nomenclature. As more and more data are compiled in digital form, the need for a comprehensive and robust corporate geological model becomes apparent.

Several factors are driving the need to develop a corporate geological data model. Computers have now become an essential tool for acquiring, analyzing, publishing and archiving geological data. The use of the Internet to communicate and share information has exploded in recent years. There is an increased need to integrate geological data for environmental, land use and cultural applications (Commission for the Management and Application of Geoscience Information 2003). Our clients want to be able to query our geology across political and administrative boundaries. Geology is assuming an increased role in legal and regulatory reporting. Geological surveys are striving to collaborate more with universities and the private sector (i.e., Discover Abitibi Initiative, Lake Nipigon Region Geoscience Initiative).

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[2] developing a standard vocabulary (data dictionaries or lexicons) and framework among the geological characteristics being described (entity–relationship diagrams).

[3] expanding the data model to be able to generalize or reclassify the geology based on the scale of observation.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.17-1 to 17-7.

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The benefits of implementing a common data model accrue through the entire data life cycle[4] (Wahl, Soller and Yeldell 2000). Map creation would be more efficient if a core set of attributes are collected using a common language. Data analysis would be easier with compatible data formats and attributes. Geologists spend 40 to 70% of their time "massaging" (reformatting, reprojecting, recompiling, etc.) their data before analysis can be done (Morrison 2004). Compilation would be far less time-consuming when merging maps, allowing the compiler to concentrate on the geological problem being addressed. Map publication would be more streamlined if the publication process received the data in a common format. Data quality would improve through the use of a common vocabulary. Geological maps could be exchanged more readily among different organizations. Providing the data model is sufficiently robust, map generalizations, reclassifications and derivative maps could be more easily produced. Integration of disparate geological data would be accomplished almost seamlessly.

WHAT EXACTLY IS A CORPORATE DATA MODEL?

A data model consists of 2 parts (North American Geological Map Data Model Steering Committee (NADM) 2003): 1) the grammar or schematics of the data model (i.e., how the various geological features relate to each other) and 2) the science language or vocabulary used to populate the various geological features being examined. The model provides a framework to store geological map data and associated legend information. As with software standards, a standard data model would require virtually no translation to become useful to the user community. The data model needs to be robust, with the capability to either handle most types of geologic information and to allow extensions that will in no way compromise the core model.

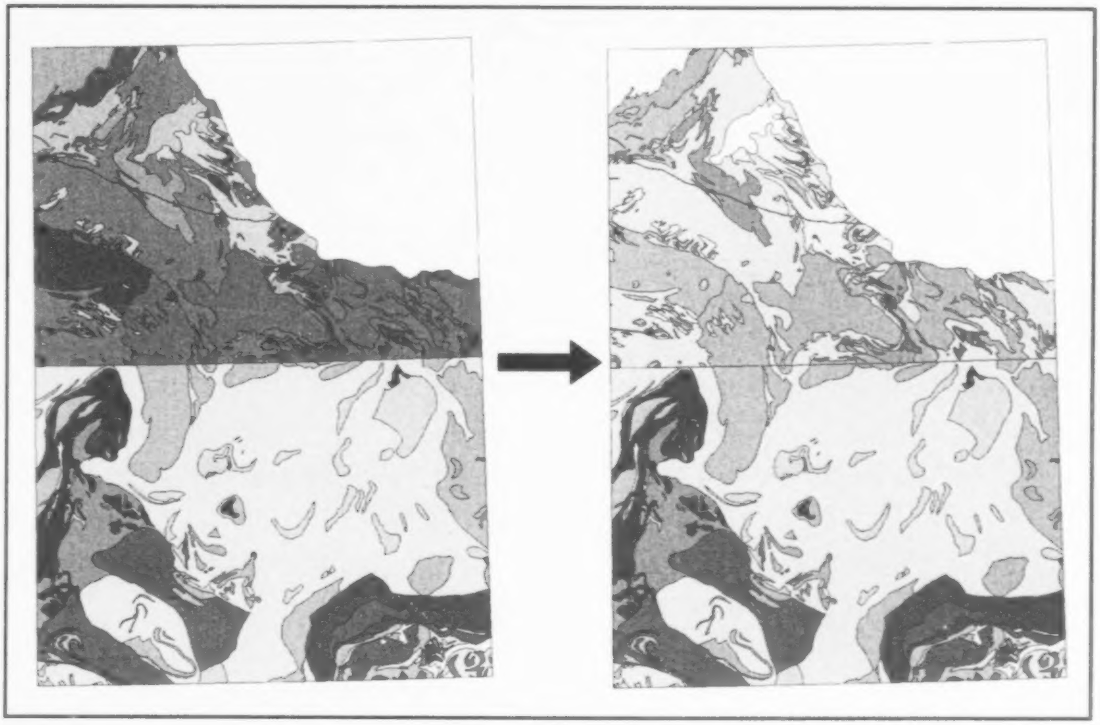

Figure 17.1. In contrast to creating data silos, a corporate geological data model would allow easy integration of diverse geological maps.

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[4] acquire–analyze–disseminate–archive

The framework or "grammar" of a geological data model is generally developed in stages, beginning with a requirements analysis and conceptual data model—a high-level catalogue of the geological objects and how they relate to each other. Figure 17.2 is an example of a high-level model developed by the North American Geological Map Data Model Steering Committee (2003). A high-level model is then driven down to a logical model where the thematic relationships are expanded to create the actual database tables and fields as well as their linkages to each other[5]. The final step to developing a working framework is to map the logical model entities to a physical model, that is , the actual software and hardware architecture chosen to store the data. For example, the PGS software environment during data acquisition, analysis and publication is the ESRI® ArcGIS® geodatabase format, which is a fully relational database environment using the Microsoft® Access database engine. The project data would eventually be moved over to a more robust corporate database environment such as Oracle® for archiving and electronic dissemination. Once the physical model is established, documentation in the form of user manuals would be required to properly understand and use the model and its related software tools.

With regards to science language, there is a "…current lack of a 'standard' for rock nomenclature that is well accepted by Canadian geologists, and the multidimensionality that persists in most of the draft rock-naming schemes that have been proposed or are in preparation. This feature of rock names will continue to hamper the construction of simple queries for map units based on lithology and the production of simple, derivative maps based on a single theme." (Davenport et al. 2002).

Several geological surveys and international committees are at various stages of developing the science language needed for a corporate data model[6]. Géologie Québec released a comprehensive lithologic vocabulary in the late 1980s with later revisions that became the standard for mapping in that province (Sharma 1996). The British Geological Survey published a rock classification scheme for

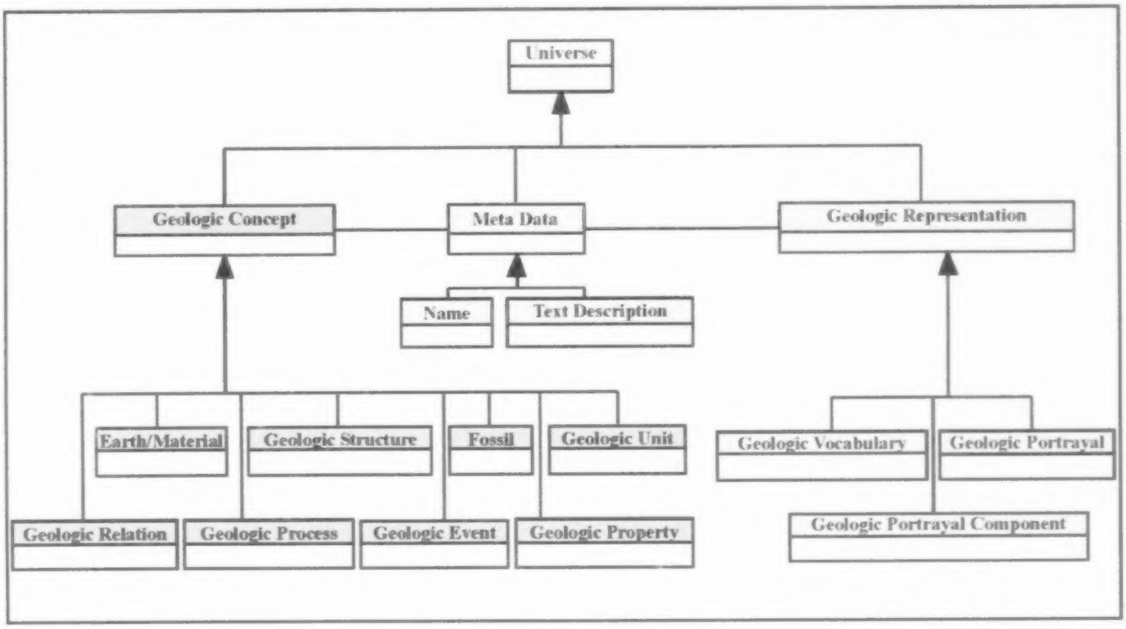

Figure 17.2. Example of a high-level data model developed by the North American Geological Map Data Model Steering Committee (2003).

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[5] Idaho Geological Survey example (http://www.idahogeology.org/Lab/pdf_files/DataModel/connection-5-7-02.pdf)

[6] Corporate geological dictionaries need a well-defined scope—with text definitions—formal definitions that are rooted in the standard science vocabulary and correlation of each term with specific related terms (Richard 2004).

igneous, sedimentary and metamorphic rocks as well as for glacial material in 1999 (http://www.bgs.ac.uk/bgsrcs/home.html [7]). In 2002, the Geological Survey of Canada (GSC) proposed a rock classification scheme based on the rock composition, texture and fabric (Struik et al. 2002). The United States Geological Survey is developing a similar lexicon of lithologic terms under the auspices of the North American Geological Map Data Model, Science Language Technical Team (http://geology.usgs.gov/dm/steering/teams/language/charter.shtml; Richard, Matti and Soller 2003). To date, draft versions of the metamorphic and sedimentary lexicons have been circulated for comment. The International Union of Geological Sciences (IUGS) has recently established the Commission for the Management and Application of Geoscience Information (CGI) to support best practices in geoscience information applications and to encourage the development of geoscience standards. In 2003, CGI formed a working group to create a new multilingual thesaurus for the geosciences to enable the global exchange of geoscience information with the help of a common core vocabulary (http://www.bgs.ac.uk/cgi_web/tech_collaboration/mlt/thesaurus.html).

WHERE DO WE GO FROM HERE?

At present, the PGS "Fieldlog" data model (Figure 17.3) deals with a small portion of the geological information that would be incorporated into the corporate data model, namely, the point or outcrop data[8] acquired during the bedrock mapping program. Subsequent interpretation and analysis of the outcrop information in conjunction with other thematic data (geophysics, geochemistry, satellite imagery, etc.)

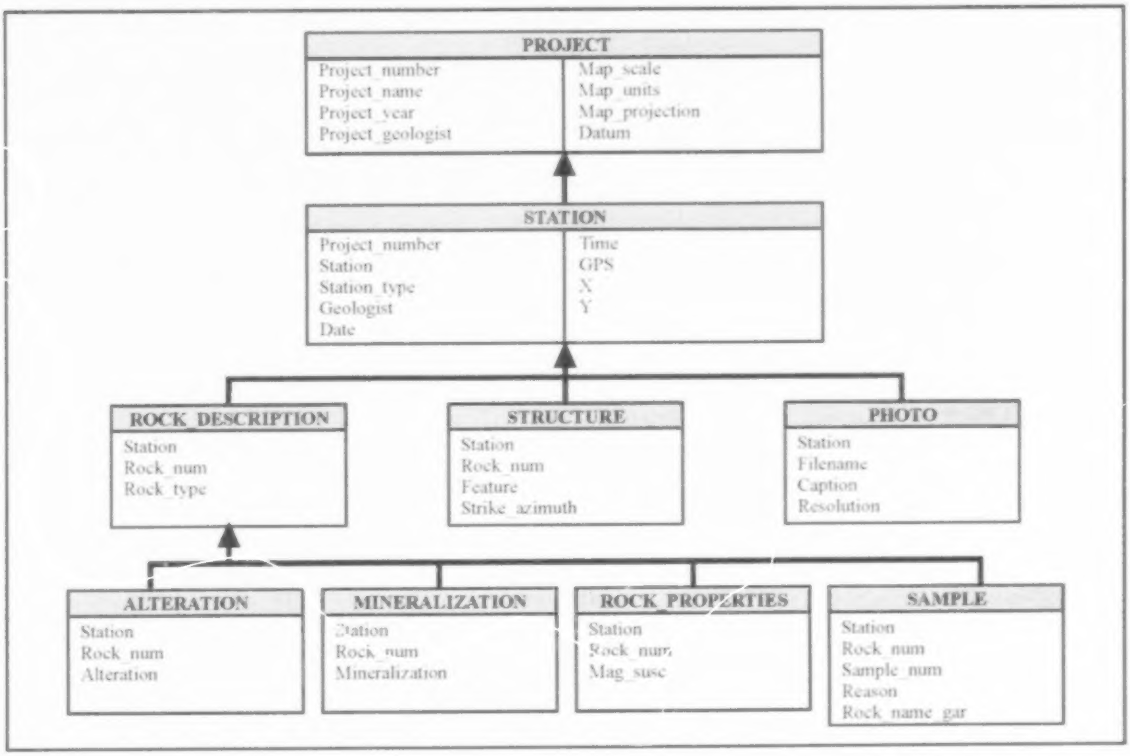
PROJECT
Project_number
Project_name
Project_year
Project_geologist
Map_scale
Map_units
Map_projection
Datum
STATION
Project_number
Station
Station_type
Geologist
Date
Time
GPS
X
Y
ROCK_DESCRIPTION
Station
Rock_num
Rock_type
STRUCTURE
Station
Rock_num
Feature
Strike_azimuth
PHOTO
Station
Filename
Caption
Resolution
ALTERATION
Station
Rock_num
Alteration
MINERALIZATION
Station
Rock_num
Mineralization
ROCK_PROPERTIES
Station
Rock_num
Mag_susc
SAMPLE
Station
Rock_num
Sample_num
Reason
Rock_name_gar

Figure 17.3. Typical PGS "Fieldlog" data model: a simplified schematic of the data model presently being populated.

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[7] Note that access to links in this paper were verified October 18, 2004.

[8] The OGS has already developed a corporate library of structural point symbols (Jackson, Muir and Romkey 1995).

help the geologist produce the line data[9] (contacts, faults, folds, etc.) and polygon data (map units, alteration zones, metamorphic terranes, etc.) that make up a typical geological map. The corporate geological data model has to be able to store all the above information into one coherent whole. To assure maximum interoperability, the PGS geological data model will have to incorporate the North American Data Model[10] framework, which is still under development.

In addition to being interoperable, the model has to be "scalable", that is, it has to allow for the "informal" map units to be hierarchically aggregated into progressively more general groupings and for lithologically defined map units to be correlated to their chronostratigraphic equivalents (Figures 17.4 and 17.5). The GSC has developed a database tool (*MapLith*) to organize legend information and apply a variety of classifications (Davenport 2004). To work properly, *MapLith* requires a fairly comprehensive and up-to-date lexicon of lithostratigraphic and chronostratigraphic names for the province. The Ontario contribution to the Lexicon of Canadian Geological Names (http://cgkn1.cgkn.net/weblex/weblex_e.pl) is a key component to the PGS geological data model, allowing the geological data to be generalized and merged with other data sets both within and outside Ontario's borders. The existing lexicon for Ontario is approximately 30% complete and requires extensive editing and upgrading. A recent internal workshop on OGS information management gaps highlighted the work on the Ontario lexicon as an important priority.

Because of the complexity of the science language issue, developing standards for the PGS geological data model will require continued management support, collaboration by all geoscientists and a time line of several years to complete. As such, the PGS geological data model will be built in stages. Small working groups of PGS geoscientists are developing standard lexicons for the many rock qualifiers needed in field data collection, including *alteration, bed_sorting, bed_thickness, deform_mineral, deform_phase, form, grain_size, intensity, lab_method, look_direction, metamorphic_grade, mineral, mineralization, origin, resolution, sample_reason, scale, shear_sense, shear_sense_criteria, structure, texture, top_criteria, top_direction.* At the same time, PGS will continue to monitor the development of internationally accepted rock classification schemes that a committee of senior PGS geoscientists can then adopt in whole or in part.

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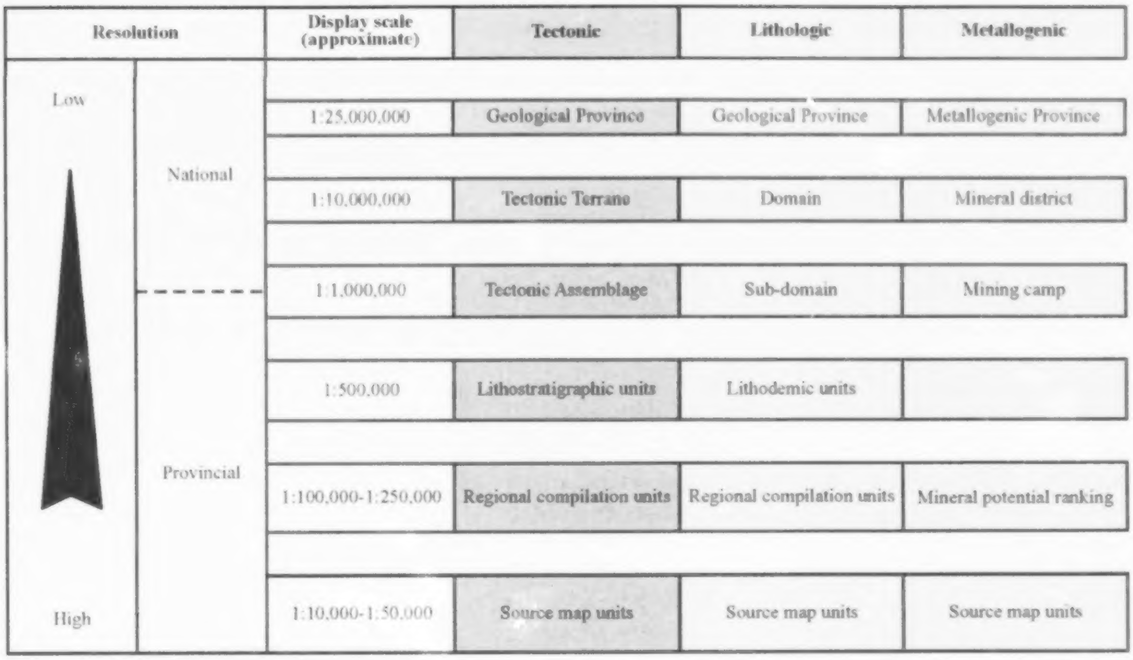
[9] The OGS has also developed a corporate library of geological line symbols (Muir, Watkins and Berdusco 2000).

[10] http://geology.usgs.gov/dm/steering_teams/design/NADM-C1.0/NADMC1_0.pdf



Resolution		Display scale (approximate)	Tectonic	Lithologic	Metallogenic
Low	National	1:25,000,000	Geological Province	Geological Province	Metallogenic Province
		1:10,000,000	Tectonic Terrane	Domain	Mineral district
		1:1,000,000	Tectonic Assemblage	Sub-domain	Mining camp
	Provincial	1:500,000	Lithostratigraphic units	Lithodemic units	
		1:100,000-1:250,000	Regional compilation units	Regional compilation units	Mineral potential ranking
High		1:10,000-1:50,000	Source map units	Source map units	Source map units

Figure 17.4. Map legend hierarchies, incorporating hierarchies into the geological data model, would allow the map data to be scaled, that is, aggregating or re-classifying the geology based on the scale of investigation (Davenport et al. 2002).

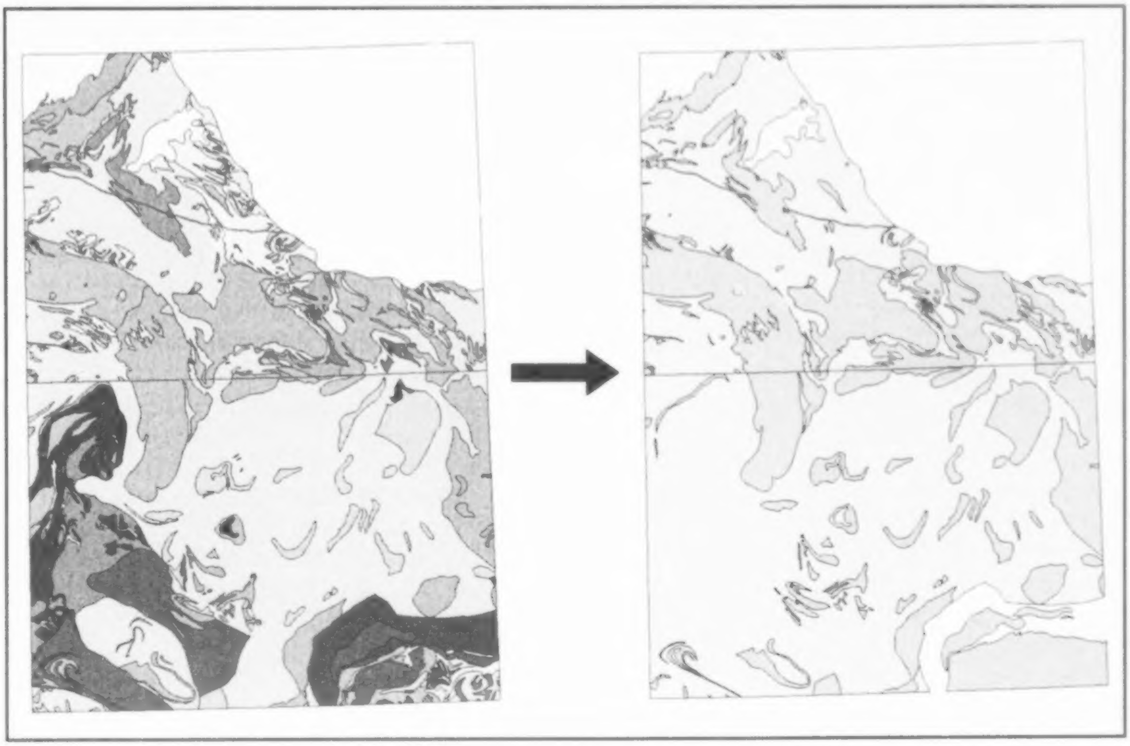


Figure 17.5. An example of a scalable map: map units from Figure 17.1 are "aggregated" into more general lithostratigraphic or chronostratigraphic equivalents.

Resolution		Display scale (approximate)	Tectonic	Lithologic	Metallogenic
Low	National	1:25,000,000	**Geological Province**	Geological Province	Metallogenic Province
		1:10,000,000	**Tectonic Terrane**	Domain	Mineral district
		1:1,000,000	**Tectonic Assemblage**	Sub-domain	Mining camp
	Provincial	1:500,000	**Lithostratigraphic units**	Lithodemic units	
		1:100,000-1:250,000	**Regional compilation units**	Regional compilation units	Mineral potential ranking
High		1:10,000-1:50,000	**Source map units**	Source map units	Source map units

Figure 17.4. Map legend hierarchies, incorporating hierarchies into the geological data model, would allow the map data to be scaled, that is, aggregating or re-classifying the geology based on the scale of investigation (Davenport et al. 2002).

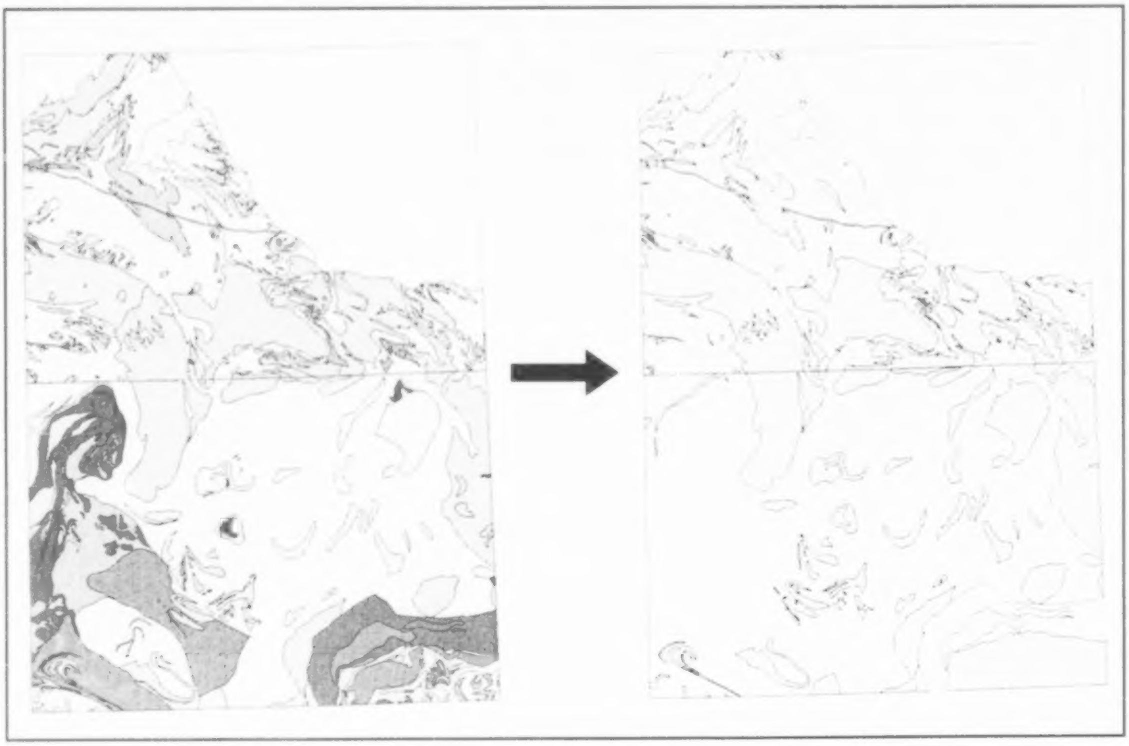


Figure 17.5. An example of a scalable map: map units from Figure 17.1 are "aggregated" into more general lithostratigraphic or chronostratigraphic equivalents.

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Sedimentary Geoscience Section

18. Project Unit 04-033. Aggregate Resources Inventory Project. District Municipality of Muskoka, Southern Ontario

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INTRODUCTION

During the summer of 2004, the Sedimentary Geoscience Section of the Ontario Geological Survey (OGS) conducted a field investigation in support of an aggregate resources inventory in the District Municipality of Muskoka, southern Ontario (Figure 18.1). Previous aggregate investigations in this area took place in the early 1980s and 1990s (Staff of the Algonquin Region 1983; Ontario Geological Survey 1990). These studies require revision and updating as extensive extraction activities during the last 2 decades have led to a progressive depletion of sand and gravel resources within the study area (Jagger Hims 1998a, 1998b). Also, new data from more recent regional geological mapping have become available (Bajc and Henry 1991; Bajc and Paterson 1992a, 1992b; Lumbers and Vertolli 2000a-d, 2003; Lumbers, Vertolli and Schwerdtner 2000a, 2000b; Easton 2001a, 2001b) that can be incorporated into an updated aggregate resources inventory. At the time of writing, the study area has not been designated under the *Ontario Aggregate Resources Act (1989)*.

The purpose of the current project is to delineate and define the aggregate resource potential and to evaluate the quantity and quality of both the sand and gravel and the bedrock resources within the study area. This information can be used for planning associated with infrastructure development, land use and economic development.

The District Municipality of Muskoka consists of Georgian Bay, Muskoka Lakes and Lake of Bays townships and the towns of Huntsville, Bracebridge and Gravenhurst. The region has a population of 53 106 and covers an area of 3890 km^2 (Statistics Canada 2004). It borders the Parry Sound and Nipissing districts to the north and northeast, Haliburton District to the east, and Simcoe and Peterborough counties to the south and southeast. The main community centres in Muskoka are Bracebridge, Huntsville, Gravenhurst and Bala. Major highways traversing this area include the north-south aligned Highways 69/400 and 11, and easterly trending Highways 141, 169, 60, 118 and 117 (*see* Figure 18.1). The scenic landscape, the presence of more than 1000 lakes and Muskoka's proximity to Toronto have combined to make the region one of the most popular recreational areas in Ontario.

The majority of the study area falls within the Georgian Bay Fringe and Algonquin Highlands physiographic regions. A third physiographic unit, the north-trending Number 11 Strip, bisects the Algonquin Highlands region within the study area (Chapman and Putnam 1984). The former 2 regions are characterized by bare or thin-drift covered knobs and ridges of Precambrian bedrock. The Algonquin Highlands, however, has a higher surface relief and less exposed bedrock. In contrast to these regions, the Number 11 Strip, which is only a few kilometres wide, has a subdued landscape with the surficial materials often consisting of sandy and, locally, gravelly deposits. Highway 11, after which the region is named, is located along this depression.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.18-1 to 18-9.

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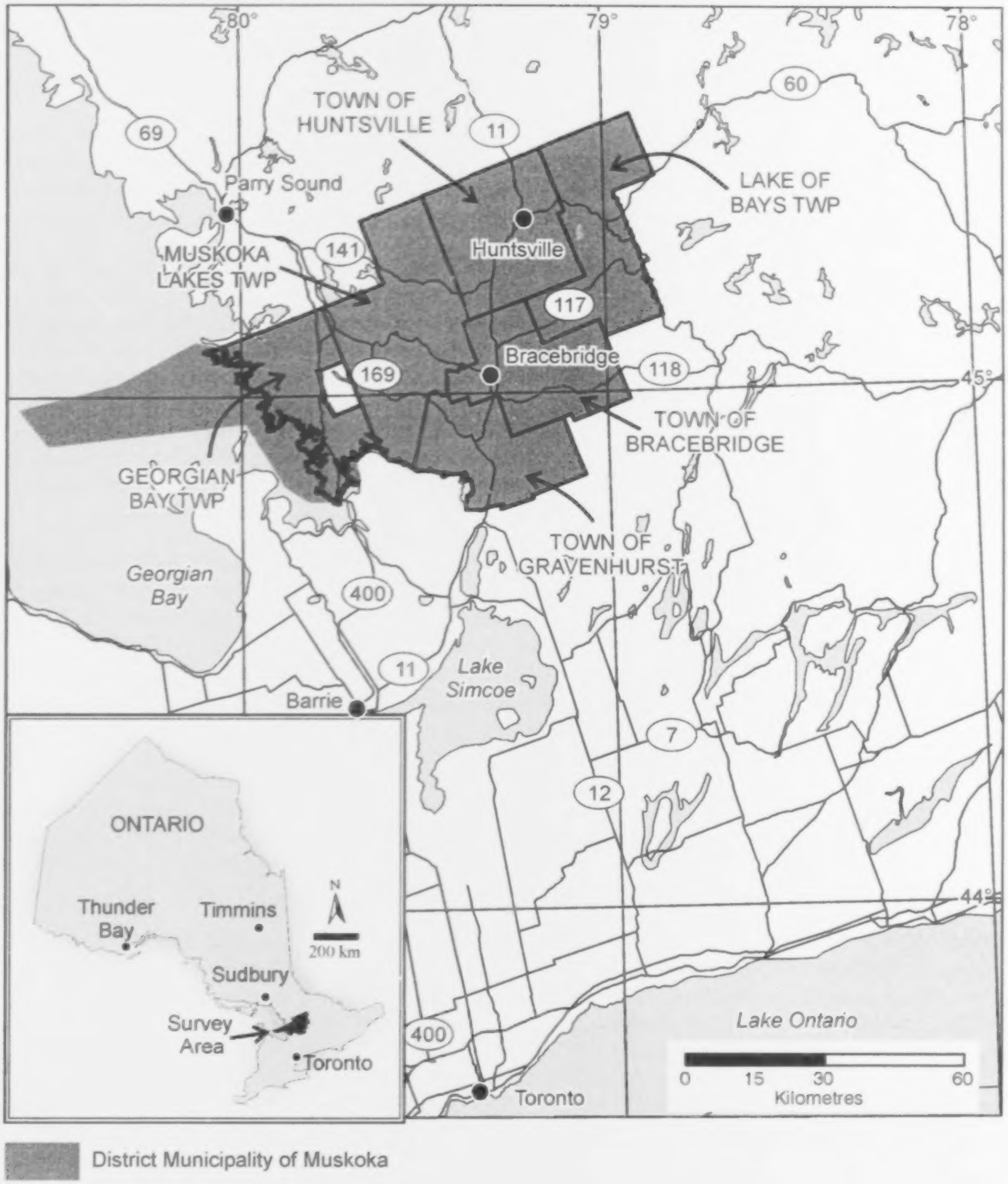
80°
79°
78°
45°
44°
60
69
11
TOWN OF HUNTSVILLE
LAKE OF BAYS TWP
Parry Sound
Huntsville
141
MUSKOKA LAKES TWP
117
Bracebridge
118
169
TOWN OF BRACEBRIDGE
GEORGIAN BAY TWP
TOWN OF GRAVENHURST
Georgian Bay
400
11
Lake Simcoe
Barrie
7
12
ONTARIO
Thunder Bay
Timmins
N
200 km
Sudbury
Survey Area
Toronto
400
Lake Ontario
0
15
30
60
Kilometres
Toronto
District Municipality of Muskoka

Figure 18.1. Location map of the survey area.

BEDROCK GEOLOGY AND AGGREGATE POTENTIAL

Bedrock Geology

The study area, located in the Central Gneiss Belt (CGB) of the Grenville Province, is dominated by polycyclic, quartzofeldspathic gneisses chiefly of igneous origin at amphibolite- and, locally, granulite-facies metamorphic grade. Within the CGB, lithotectonic terranes have been identified on the basis of rock types, internal structure, metamorphic grade, geological history and, locally, geophysical signature. Easton (1992) has provided a systematic overview of the Grenville Province and detailed descriptions of the terranes and their subunit domains. Recent geological mapping at a 1:50 000 scale provides the basic geological information for this area (Lumbers and Vertolli 2000a-d, 2003; Lumbers, Vertolli and Schwerdtner 2000a, 2000b; Easton 2001a, 2001b).

The southern parts of the Algonquin and Parry Sound terranes occur in the study area. The Algonquin Terrane, formed 1800 to 1600 and/or 1500 to 1400 Ma, is characterized by felsic to intermediate gneisses and migmatites (cf. Easton 1992). The Parry Sound Terrane consists primarily of intermediate to mafic gneisses with a north- to northwest-trending fabric and is dated at 1450 to 1350 Ma.

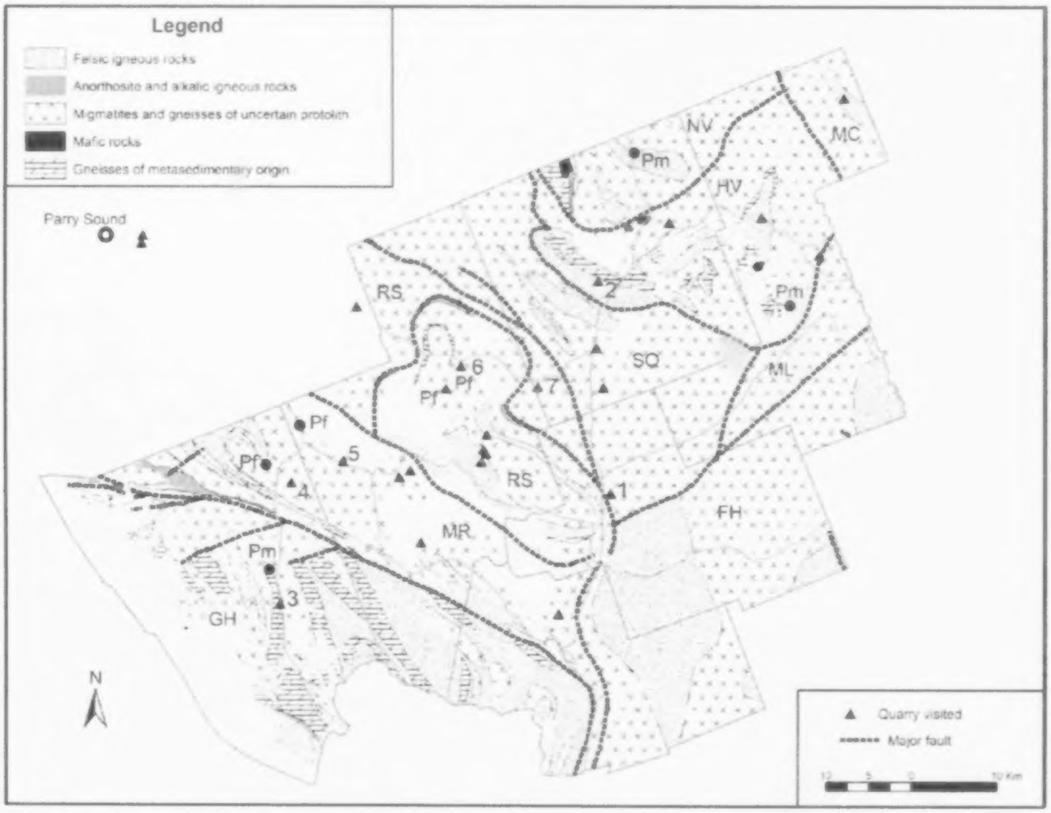
Legend
Felsic igneous rocks
Anorthosite and alkalic igneous rocks
Migmatites and gneisses of uncertain protolith
Mafic rocks
Gneisses of metasedimentary origin
Parry Sound
NV
MC
Pm
HV
RS
2
Pm
SQ
ML
6
Pf
Pf
7
Pf
5
Pf
4
RS
1
FH
MR
Pm
3
GH
N
Quarry visited
Major fault
10 5 0 10 Km

Figure 18.2. Bedrock geology, Muskoka District illustrating fault-bounded domains. Legend: GH: Go Home; RS: Rosseau; FH: Fishog; HV: Huntsville; NV: Novar; ML.: McClintock; MR: McCraney; MR: Moon River; SQ: Seguin (*modified from* Easton 1992). Key for quarry names: 1. Rosewarne; 2. Hutchenson; 3. Gibson; 4. MacTier; 5. SeegMiller; 6. Brent; 7. Millers. Plutons are indicated by P with black dots or triangles: f-felsic; m-mafic.

These terranes are intruded locally by felsic to mafic plutons that show less deformed textures than the host rocks. Within the study area, 9 lithotectonic subunits are recognized, namely, Go Home, Rosseau, Fishog, Huntsville, Novar, McClintock, McCraney, Moon River and Seguin domains (Figure 18.2). The first 7 domains belong to the Algonquin Terrane and the last 2 to the Parry Sound Terrane.

The bedrock geology of the study area is, in terms of lithology and potential aggregate usage, extremely varied. This is a result of the polycyclic metamorphism that took place during the long geological history of the Meso- to Neoproterozoic. The gneissic and migmatitic rocks exposed in outcrops often show well-developed foliation and strong banding structures. Platy minerals such as mica are sometimes enriched along the banding surfaces, in particular, in gneisses that have distinct platy and schistose structures. A lack of lithologic consistency among neighbouring exposures is commonly observed. Because of these factors, many of the gneissic rocks are prone to weathering and tend to separate along banding surfaces. Weathered, "crumbly" mesocratic gneisses were observed in the uppermost 10 to 20 cm of rock exposures at several sites (Photo 18.1). Rocks suitable for producing high-quality crushed stone products are often limited in extent and are difficult to outline at a regional-mapping scale.

Aggregate Potential

Many of the operational quarries in the study area produce low-quality crushed stone products, equivalent to Granular A and B, mainly for non-commercial customers. The bedrock in the area is capable of producing a large quantity of granular aggregates based on studies conducted by the Ontario Ministry of Transportation (MTO) (Jagger Hims 1998 a-d). In addition, less-deformed plutonic blocks, suitable or having potential for asphalt aggregates, have been noted in the study area, in fact, some quarries extracting mafic gneisses are approved for asphalt aggregates such as HL1 ("hot laid") and 4. These observations suggest that site specific investigations and laboratory testing are key factors in locating rocks suitable for asphalt aggregates and for ensuring consistent high quality.

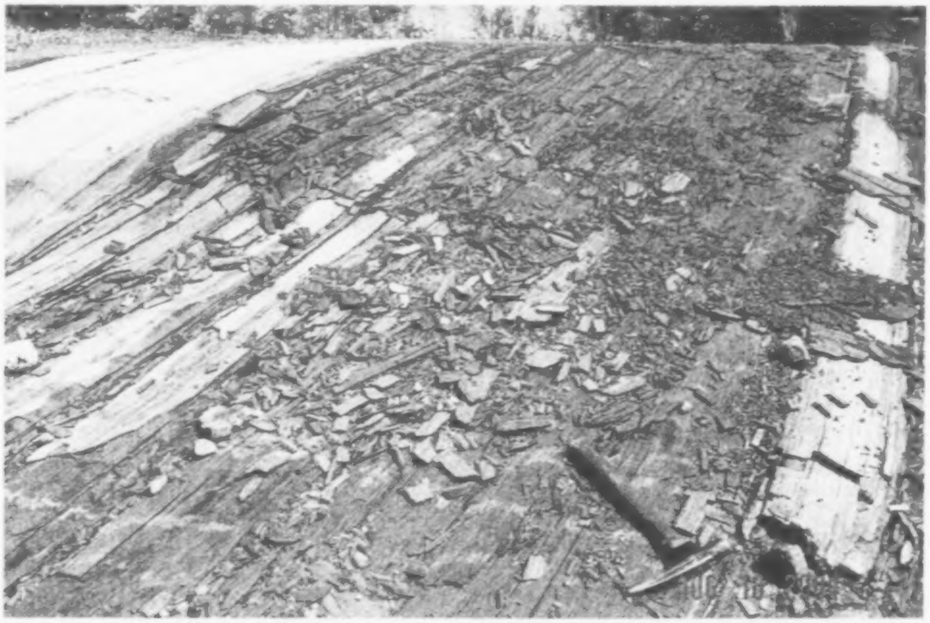

Photo 18.1. Gneissic rock outcrop; note the "crumbly" weathered surface. Hammer is 35 cm in length.

Two quarries situated along Highway 11 supply a wide range of crushed stones for both local and regional markets. At Bracebridge, the Rosewarne Quarry, operated by Fowler Construction Co. Ltd., produces DFC, HL1 and other asphalt and granular products from a mafic to intermediate gneiss (*see* Figure 18.2). The rock appears consistent with that of the surrounding area and the current quarry may be expanded. The Hutchenson Quarry, which also produces sand and gravel, is located southwest of Huntsville (*see* Figure 18.2). It has been approved by MTO for DFC ("dense friction course"), HL1 and other crushed stone products. The quarry is located in a rock ridge containing a metagabbro core that probably crops out to the east in the road cuts of Highway 11. The gabbro is flanked by west-northwest-trending, intermediate gneissic rocks.

Along Highway 69/400, the Gibson and MacTier quarries have, historically, been 2 major sources for crushed aggregate in the study area. However, the former, which produced HL3 from a rock ridge composed of massive, mesocratic gneiss, has been closed. Extraction of granodioritic gneiss from a rock ridge in the latter quarry is the current operation. However, at the time of field investigation, the MacTier Quarry was slated for closure because of resource depletion. The only quarry in full production in the study area, within 5 km of Highway 69/400, is the SeegMiller Quarry operated by Fowler Construction Co. Ltd.; this quarry is located off Highway 169. This quarry, which produces granular aggregates from granitic and dioritic gneiss, has the potential for asphalt products. At the time of field investigation, the quarry had been approved by MTO for, but has not yet supplied, asphalt aggregate products to provincial highway construction.

Laboratory tests indicate that the felsic to mafic plutonic rocks identified along Highways 69/400 and 11 (*see* Figure 18.2) have the potential to be used in high-quality asphalt products (Jagger Hims 1998a-d). The dioritic pluton north of the Gibson Quarry (*see* Figure 18.2) was re-checked to the east, across Highway 69/400, along Muskoka Road 38. Ministry of Transportation documents indicate that this rock has a PN("petrographic number") of 103 to 119, but a high loss of 40% in a Los Angeles abrasion test. To assess the pluton's potential for high-quality crushed aggregate production, the bedrock was re-sampled; currently MTO laboratory testing is in progress.

The felsic pluton northwest of the MacTier Quarry is a deformed, pinkish granite, located near the municipal landfill site (*see* Figure 18.2). This body is a few hundred metres long, 50 to 100 m wide and dips moderately to the northeast. It is flanked to the east by intermediate gneiss. Testing, by MTO, of a sample taken from the eastern flank of the pluton indicates potential for use in HL1 (Jagger Hims 1998a, sample 98-69-12).

Along Highway 141, 2 quarries are extracting granitic and dioritic rocks (*see* Figure 18.2). The Brent Quarry crushes a massive, pink granite from a moderately southeast-dipping ridge that extends for a few hundred metres (Photo 18.2). The fine- to medium-grained granite is hard and durable with low metamorphic grade. To assess its potential use in asphalt, this rock was sampled for MTO laboratory testing. The Miller Quarry is located in a rock ridge consisting of mafic-rich gneiss that dips moderately to the south. A less deformed dioritic rock core occurs in the centre of the ridge, whereas, the flanks are characterized by hard, intermediate gneissic rocks with moderate banding. These rocks appear to have the potential to produce asphalt aggregate products. This company operating the quarry was at the time of investigation, waiting for MTO's approval for the production of high-quality aggregates for use in highway construction.

The thinly bedded or flaggy nature of some gneisses within the study area may allow their extraction for decorative stone. For example, the northern part of the Huntsville Domain (*see* Figure 18.2) contains a succession of thin, highly flattened gneisses that are quarried for flagstone at 2 sites along Highway 60.

In summary, intrusive rocks or plutons occur locally throughout the study area. These rocks have the potential to be used in asphalt and other high-specification aggregate products. The plutons often have limited extent and may not be represented on regional geology maps. They can be identified through detailed field investigations, however, their suitability for use as aggregates must be established through laboratory testing. Some crushed bedrock products, such as those used in surface paving (asphalt), require the application of anti-stripping chemical agents to overcome bonding problems caused by glassy cleavages and fracture surfaces inherent in minerals such as feldspar and quartz. Low-quality granular aggregates are abundant in the study area and, as demonstrated by the distribution of existing quarries, may occur in various gneissic rocks. However, laboratory testing is imperative to determine their suitability for high-end applications such as use in provincial highways.

SURFICIAL GEOLOGY AND AGGREGATE POTENTIAL

Surficial Geology

The surficial sediments and landscape of the study area are strongly shaped by the Late Wisconsinan glaciation. Glacial till was deposited during advance and retreat of the ice sheet which, in general, flowed to the south and southwest. In front of the receding ice margin, glaciofluvial and glaciolacustrine sediments were deposited in meltwater channels and lakes. As the ice sheet retreated to the north, much of the study area was progressively inundated by glacial Lake Algonquin at circa 11 500 years BP (Eschman and Karrow 1985). With the shifting of outlets, the lake declined in elevation and left a sequence of low-level beaches. Re-submergence of part of the area took place during the Nipissing stage at circa 5000 years BP. Present levels of the Great Lakes were achieved sometime after 3000 years BP. Various deposits associated with the glacial lakes were formed, including deep water silt-rich deposits, beach and near shore sandy deposits, deltaic and subaqueous fan sand and gravels (Barnett 1992; Ontario Geological Survey 2003).

Photo 18.2. Rock ridge of massive, pinkish granite, occasionally containing dark-coloured mafic inclusions, at the Brent Quarry, Ulswater.

Much of the study area, in particular that portion along Highway 69, is barren of drift or covered with a thin veneer of till. Lacustrine and glaciofluvial deposits are limited in extent and are often located in low-lying bedrock depressions (Figure 18.3). Extensive glaciofluvial outwash sand and gravel deposits occur along Highway 11 (Staff of the Algonquin Region 1983; Ontario Geological Survey 1990). Because of its unique nature and the fact that it separates surrounding bare bedrock terranes, Chapman and Putnam (1984) identified this area as a physiographic region naming it the Number 11 Strip.

Aggregate Potential

Among the more than 200 pits visited during the course of field work (*see* Figure 18.3), most are located in areas previously identified as selected resource areas (Staff of the Algonquin Region 1983; Ontario Geological Survey 1990) and only a few are active. Field investigation indicates that crushable granular resources are depleted in most areas due to extensive extraction and cultural constraints. Within the study area, there are no remaining sand and gravel resources capable of supplying large volumes of crushable granular materials, although, some deposits still provide a certain amount of crushable granular material. These deposits, however, are often located in remote areas where long haul distances and/or primitive roads impose constraints on resource utilization. Pits in these areas are intermittently active and the resources extracted are used mainly for local road maintenance.

Gravel-rich deposits in pits contain, without exception, a noticeable amount of weathered, "crumbly" gneissic clasts that often have a schistose structure. The existence of such clasts suggests the unsuitability

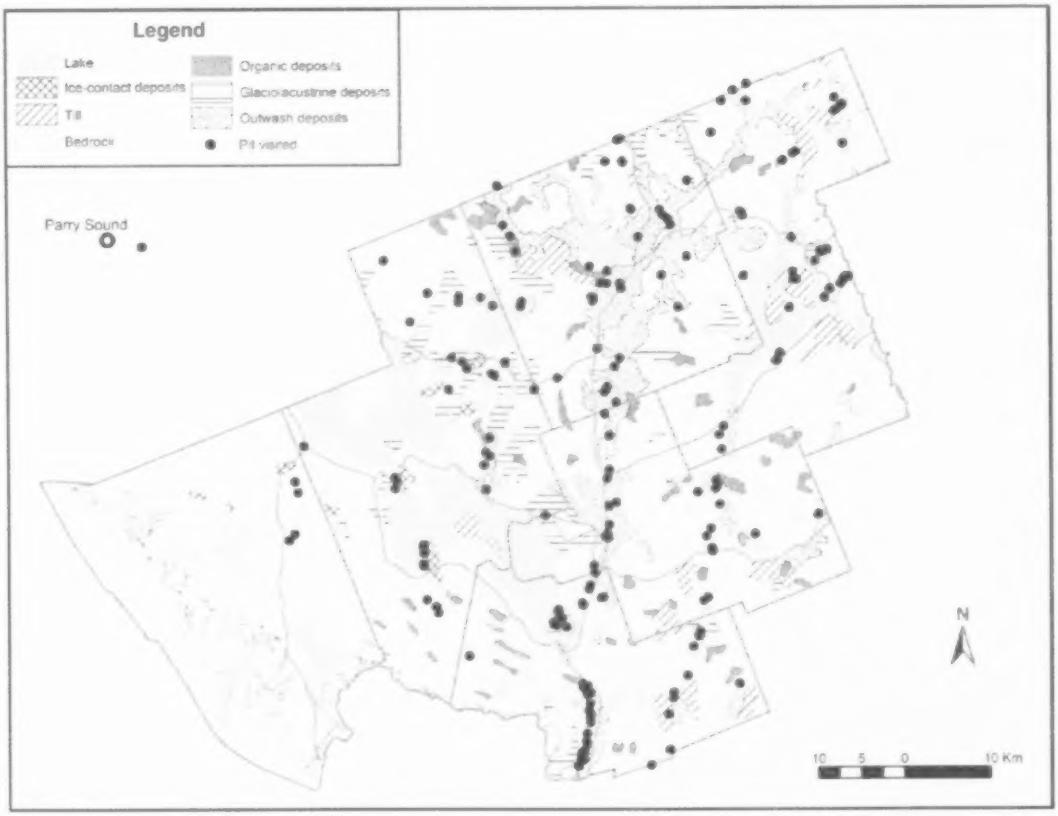

Figure 18.3. Surficial geology, Muskoka District.

of the deposits for the production of high-quality aggregate products. Since such deleterious rock fragments were observed more commonly in inactive pits, it is clear that weathering has occurred on extracted granular materials that have been exposed for a few years to decades.

Sandy material is available in relatively large quantities in subaqueous fans, deltas and lacustrine beaches and ice-contact deposits. Sand from these deposits has several uses including, but not limited to, winter road sand, septic filtering material and mortar sand. The sand material sometimes contains silt and very-fine sand and, therefore, screening and blending is often necessary. The sand deposits may not be suitable for Portland concrete use due to potential alkali-silica reactions.

CONCLUSIONS

In the study area, the easily accessible sand and gravel deposits are nearly depleted and there are no remaining undeveloped resources capable of supplying large volumes of crushable granular materials. In the future, the aggregate supplies are likely to come from bedrock sources or be imported from adjacent regions, for example, near Parry Sound or in areas south of Muskoka where crushable granular resources and bedrock suitable for quarrying are abundant.

In spite of the lithologic variability and complexity, resulting from polycyclic metamorphism, field observations and other data available indicate that the gneissic bedrock in the Muskoka area is capable of producing large quantities of mineral aggregate. High-quality aggregate products can also be produced locally, in particular, from less-deformed felsic or mafic plutons that are more consistent in composition than the surrounding rocks. The plutons often have limited extent and may not be represented on regional-scale geological maps. They can be identified through detailed field investigations, however, their aggregate suitability should be established through laboratory testing.

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19. Project Unit 02-015. Industrial Mineral Potential of the Guelph Formation and the Eramosa Member of the Amabel Formation, Southwestern Ontario

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INTRODUCTION

The Guelph Formation and underlying Eramosa Member of the Amabel Formation (= uppermost Lockport Formation) have been recognized and exploited as important dolostone rock units for the aggregates industry and as significant bedrock aquifers in southwestern Ontario for more than a century (Miller 1904; Goudge 1938; Hewitt 1960, 1964; Hewitt and Vos 1972; Derry Michener Booth and Wahl and Ontario Geological Survey 1989a, 1989b; Kelly 1996, 2001; Singer, Cheng and Scafe 1997). Aggregate production from the Amabel Formation, Eramosa Member and overlying Guelph Formation along the Niagara Escarpment exceeds 18 million tonnes per year (*Aggregates & Roadbuilding*, July/August 2004, p.17). This production occurs from 7 quarries situated predominantly in the southeast and extreme northwest portions of the Niagara Escarpment of southern Ontario (e.g., Dufferin Aggregates' Milton, Acton, and West Flamborough quarries; Lafarge Canada Inc.'s Dundas and Manitoulin quarries; and Nelson Aggregate Co.'s Burlington and Lincoln quarries). Significant volumes of Eramosa and Guelph lithofacies are exploited only from the Dundas, West Flamborough, and Lincoln quarries. All of the large quarries that historically exploited Guelph, Eramosa and Amabel lithofacies from the Guelph–Cambridge areas are now abandoned. The Glenchristie and Guelph Dolime quarries between Guelph and Hespeler were major suppliers of dolime and dolomite for the chemical industry. There has been a steady annual increase in the demand for pure dolomites on the order of 2 to 5% over the past decade, especially in the flat-glass industry. Key uses for deadburned dolomite are in the steel industry, whereas dolime and dolomite are sources of CaO and MgO in agriculture and feedstock, magnesium oxide in refractories, glass, pharmaceuticals, fertilizers, as magnesium metal and numerous other applications (*see also* Springer 1983). The Bruce Peninsula region is the key area where dimension stone and aggregate is exploited from the Eramosa and Wiarton and Colpoy members of the Amabel Formation (Armstrong and Meadows 1988; Armstrong and Dubord 1992; Armstrong 1993a, 1993b).

In the subsurface of southwestern Ontario, the Guelph Formation has proven to be one of the most significant sources of natural gas and, to a lesser extent, oil since the first subsurface discoveries of the Guelph Formation were made in 1889. More than 150 gas and oil pools have been discovered in pinnacle and patch reefs of the Guelph Formation and basal Salina Formation, amounting to historical production in excess of 20 billion cubic metres of natural gas and 2.1 million cubic metres of oil (Armstrong, Goodman and Coniglio 2002; Coniglio, Zheng, and Carter 2003). This is equivalent to approximately 60% of Ontario's historical total gas production and 17% of its oil production, respectively. The pinnacle reefs are also used as seasonal gas storage reservoirs. New gas and oil plays and potential storage reservoirs are still being drilled on an annual basis.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.19-1 to 19-5.

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Despite the obvious economic significance of these Late Silurian age rock units to the economy of Ontario and Canada, detailed understanding of the regional lithofacies and geochemical variability within the Amabel Formation, Eramosa Member and Guelph Formation throughout the outcrop–subcrop belt and their relations to the subsurface pinnacle reef belt is lacking. The relative ages of these rock units and their regional sequence stratigraphic relations are also poorly understood. Most of the paleontological and regional stratigraphic studies of the Guelph and Amabel formations date back more than 50 to over 100 years and are in need of revision (*see* references in Logan 1863; Williams 1919; Shaw 1937; Caley 1940; Bolton 1953, 1957, 1966; Liberty and Bolton 1971; Winder 1960; Sanford 1969, 1993; Johnson et al. 1992; de Freitas, Brunton and Bernecker 1993; and Brunton et al. 1998). Recent mapping and diamond drilling by the Ontario Geological Survey on the Bruce Peninsula (Armstrong and Meadows 1988; Armstrong and Dubord 1992; Armstrong 1993a, 1993b) has revealed that the definition of the Eramosa Member of the uppermost Amabel Formation should be expanded and the Eramosa be reassigned to the basal part of the Guelph Formation. Regional mapping during the course of this field season throughout the entire outcrop–subcrop belt, in combination with core logging of 8 drill core covering an area from Tobermory to Corbetton, supports this re-interpretation of the stratigraphic relationships of the Guelph–Amabel or Guelph–Lockport throughout the Niagara Escarpment.

Regional variability in the geochemistry of these rock units throughout the outcrop–subcrop belt is also poorly constrained. The economic significance and need for a detailed stratigraphic and geochemical investigation of the Guelph Formation from an industrial minerals perspective was recently highlighted by Kelly (1996, 2001), Feenstra (1996), Feenstra and Wilson (1996), and Feenstra and Smith (1997). Current economic uses and potential industrial applications of these economically significant carbonate units beyond their current use as crushed aggregate for road metal has been recently summarized by Kelly (1996, 2001). A regional assessment of Guelph Formation dolostone purity by Dow Chemical USA of Ludington, Michigan, throughout parts of the Bruce Peninsula during the early 1990s has revealed encouraging magnesium values (21.8% MgO), combined with low averages for impurities such as SiO_2, Fe_2O_3 and Al_2O_3 (averaging 0.03%) (Feenstra 1996; Feenstra and Wilson 1996).

The initiation of this multi-year study to investigate both the industrial mineral potential of the Guelph (Eramosa) and Amabel formations and their regional significance as bedrock aquifers is in response to socio-economic pressures, including 1) increased demand annually for high-purity carbonates in the dynamic industrial minerals sector, 2) current and proposed limitations on future production and expansion of existing limestone quarries of these important Silurian rock units in the Niagara Escarpment region of the Greater Toronto Area, and 3) increased demand for delineation and understanding of sustainable groundwater resources throughout southwestern Ontario.

SCOPE OF STUDY

The entire outcrop–subcrop belt of the Guelph Formation and Eramosa member of Amabel Formation, covering an area of approximately 1000 km^2, was examined during the summer of 2004 (Figure 19.1). The three-month field season, spanning June through early September, involved the collection of more than 700 rock samples for lithologic, paleontologic, petrologic, and geochemical analyses. Approximately 522 samples have been submitted for geochemical analysis, including major oxides and zinc and lead concentrations. A number of samples for conodont analysis were collected from Ontario Geological Survey diamond-drill holes on the Bruce Peninsula to help constrain the relative ages of the Silurian formational units. Conodont samples have been sent to the Natural Resources Canada (NRCan) laboratories in Calgary for processing and analysis. The diagenetic history of the Guelph Formation, including the nature of dolomitization of the Eramosa and Guelph formations, will be the focus of an MSc thesis by Dekeyser at the University of Waterloo, under the supervision of Dr. M. Coniglio.

The main goal of the first phase of this multi-year study is to analyze the geochemistry of these rock units and assess the quality of the dolostones of the Guelph and Eramosa formational units for various industrial mineral applications throughout the outcrop–subcrop and thin-drift cover areas of southwestern

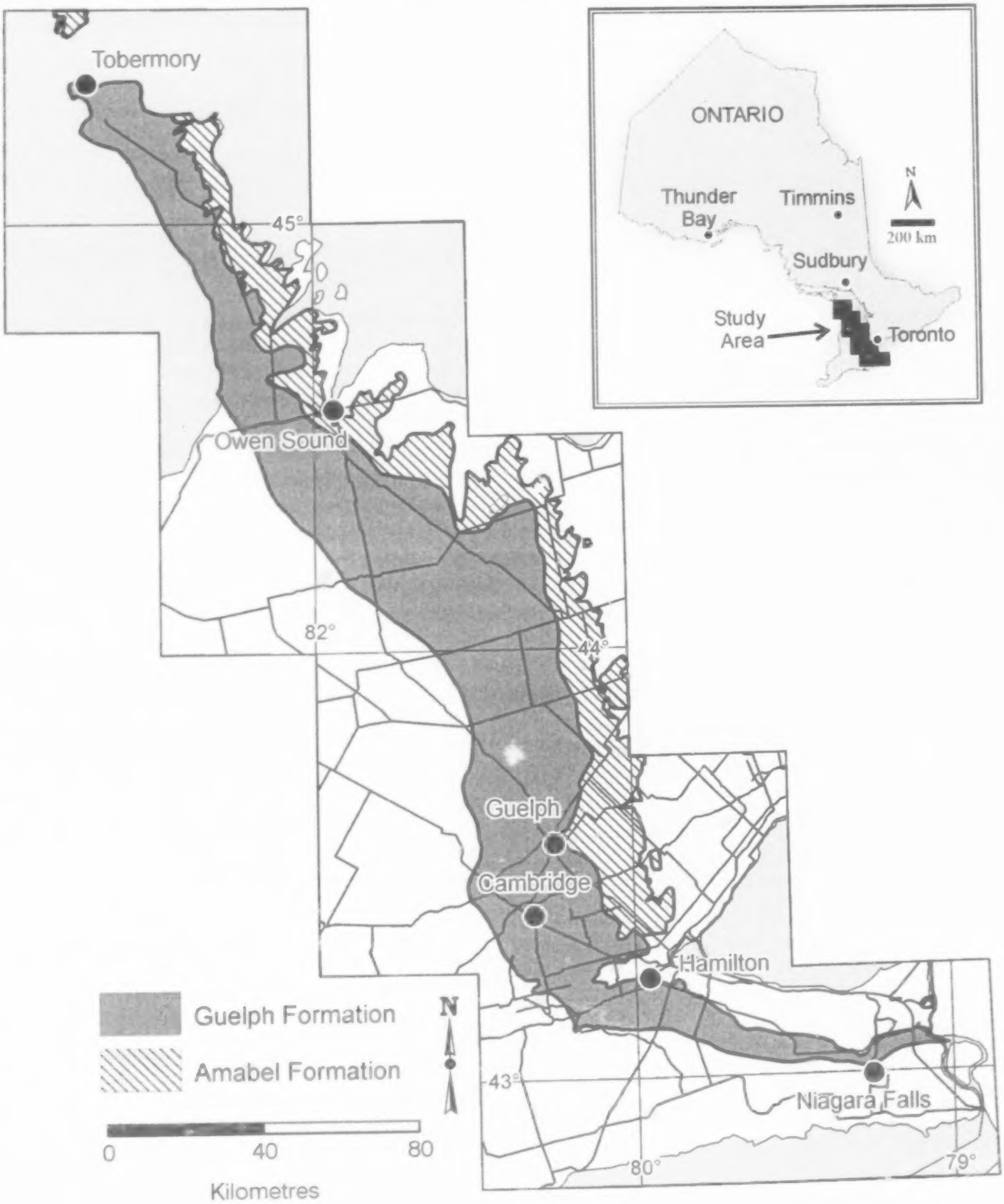
Tobermory
45°
Owen Sound
82°
44°
Guelph
Cambridge
Hamilton
Niagara Falls
43°
80°
79°
Guelph Formation
Amabel Formation
N
0
40
80
Kilometres
ONTARIO
Thunder Bay
Timmins
Sudbury
Study Area
Toronto
N
200 km

Figure 19.1. Outcrop and subcrop belt of Guelph, (Eramosa) and Amabel formations within the study area.

Ontario. This will hopefully lead to the delineation of dolostone resources between Owen Sound and Hamilton favourable for chemical and metallurgical stone applications. Southward extensions of favourable dimension-stone resources of the Bruce Peninsula may also be identified.

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20. Project Unit 04-020. Southern Ontario Hydrocarbon Resource Evaluation: Regional Stratigraphic Synthesis – A Preliminary Report

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INTRODUCTION

The Ontario Geological Survey (OGS) has been contracted to carry out a regional stratigraphic synthesis of the Paleozoic of southern Ontario, in partnership with the Ontario Ministry of Natural Resources, the Geological Survey of Canada, and the Ontario Oil, Gas and Salt Resources (OGSR) Library, as part of the Southern Ontario Hydrocarbon Resource Evaluation project. This project, funded by Natural Resources Canada through its Targeted Geoscience Initiative II program, is administered by the Ontario Oil, Gas and Salt Resources Corporation, a wholly owned subsidiary of the Ontario Petroleum Institute. Project Lead is Terry Carter, Subsurface Geologist for the Petroleum Resources Centre of the Ministry of Natural Resources, and project manager is Tony Hamblin, Research Scientist with the Calgary office of the Geological Survey of Canada. Staff of the OGSR Library provide technical assistance in all aspects of the project as well as access to its invaluable collection of subsurface geological data stored at the Library's data repository in London. The following report is a summary of the progress to-date on this project, including field work and related activities.

BACKGROUND AND PROJECT OBJECTIVES

In 1967, the Ontario Department of Energy and Resources Management published the *Guide to the subsurface Palaeozoic stratigraphy of southern Ontario* (Beards 1967). In the almost 40 years since this guide was published, over 5000 petroleum wells have been drilled in Ontario, including 450 to Precambrian basement and at least a dozen continuously cored holes (most of these were drilled by the OGS). In addition, geophysical logging technology has improved, new depositional models and methods of interpretation (e.g., sequence stratigraphy) have been developed, and revisions made to stratigraphic nomenclature. In addition, the digitization of subsurface data has enhanced their management and analysis. The main objective of the present study is to produce an updated version of the Beards (1967) publication, incorporating new subsurface data, techniques and interpretative models, and to extend the correlation of subsurface units to equivalent units to surface outcrops.

Key deliverables of this project will include a comprehensive bibliography, descriptions of each stratigraphic unit and practical criteria for identification and picking of formation contacts, descriptions of regional trends in thickness, lithology and facies, lithologic logs of reference well cuttings or cores, formation top picks based on geophysical and geologic logs for each reference well, lithologic descriptions of reference outcrops, and regional cross sections. Additional project components include identification of oil and gas-bearing intervals, use of bedrock units for aggregates or mineral extraction and documentation of the results of organic geochemical analysis of hydrocarbon samples.

Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.20-1 to 20-11.

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PROJECT METHODOLOGY AND PROGRESS TO DATE

Literature Review and Bibliography

The project commenced in the spring of 2004 with a review of pertinent literature. A bibliography was created with a total of 626 references: 94 key references, 59 historical references (pre-1954), 113 references dealing with equivalent units in adjacent jurisdictions, 48 map references, and 312 general references. Particularly significant publications include Bailey Geological Services Ltd. and Cochrane (1984a, 1984b, 1985, 1986, 1990), Beards (1967), Johnson et al. (1992), Poole et al. (1970), Sanford (1961, 1968, 1969, 1993a, 1993b, 1993c), and Sanford et al. (1985).

Identification of Issues

The next phase of the project involved the identification of problems and issues that could be addressed during the course of the project. In general, identified issues include difficulties in correlation of units from the subsurface to the surface; rationalization of geophysically based formation or unit contact picks with lithologically based (specifically from drill core) observations and interpretations; problems in recognizing key breaks in the subsurface record that may reflect depositional or erosional breaks with possible tectonic inference; and the incorporation of revised stratigraphic nomenclature. Resolving these issues is complicated by the differing styles and scales of mapping in the subsurface versus outcrop exposures.

Regional Cross Sections

As part of the project, 12 regional cross sections will be constructed along lines that parallel or cross depositional strike and regional tectonic elements, such as the Algonquin Arch and Chatham Sag. The 12 lines of section are plotted and labelled in Figure 20.1. Specific locations of segments of the lines were dependant on the availability of suitable reference wells.

Reference Wells

The principles guiding selection of reference wells for this project include depth of penetration, availability and quality of geophysical logs, quality of sample cuttings, availability of core and geographic location.

Over 20 000 petroleum exploration and development wells have been drilled in Ontario. Hard-copy records for these wells are stored at the OGSR Library (formerly the MNR Petroleum Resources Library) in London. These well records are being digitized and most are now available in a searchable geographic information system (GIS)-based database. A search of this petroleum well database yielded over 800 wells that have penetrated Precambrian basement. Preliminary selection of wells for this project was based on the proximity of wells to the lines of section outlined in Figure 20.1. Files for the wells were then searched to determine availability and quality of geophysical logs (particularly gamma-ray and neutron logs) and of drill cuttings or core. The OGSR Library is a repository for drill cuttings from over 13 000 wells and core from nearly 1000 wells and has geophysical logs for nearly 4000 wells. These data have been collected by the Canadian and Ontario governments from wells drilled by the petroleum industry dating back into the late 1800s (*see* www.ogsrlibrary.com). Data submission is mandatory.

In addition, over the last 24 years, the OGS has cored a number of drill holes to Precambrian basement at various locations in southern Ontario (e.g., Johnson, Russell and Telford 1985). These cores are stored at OGS core storage facilities in Sudbury, Sault Ste. Marie and Tweed. Some of the cores have been slabbed, with half of the core stored in the OGSR Library in London. OGS cores designated as reference wells for this study are being slabbed for archival storage in the OGSR Library.

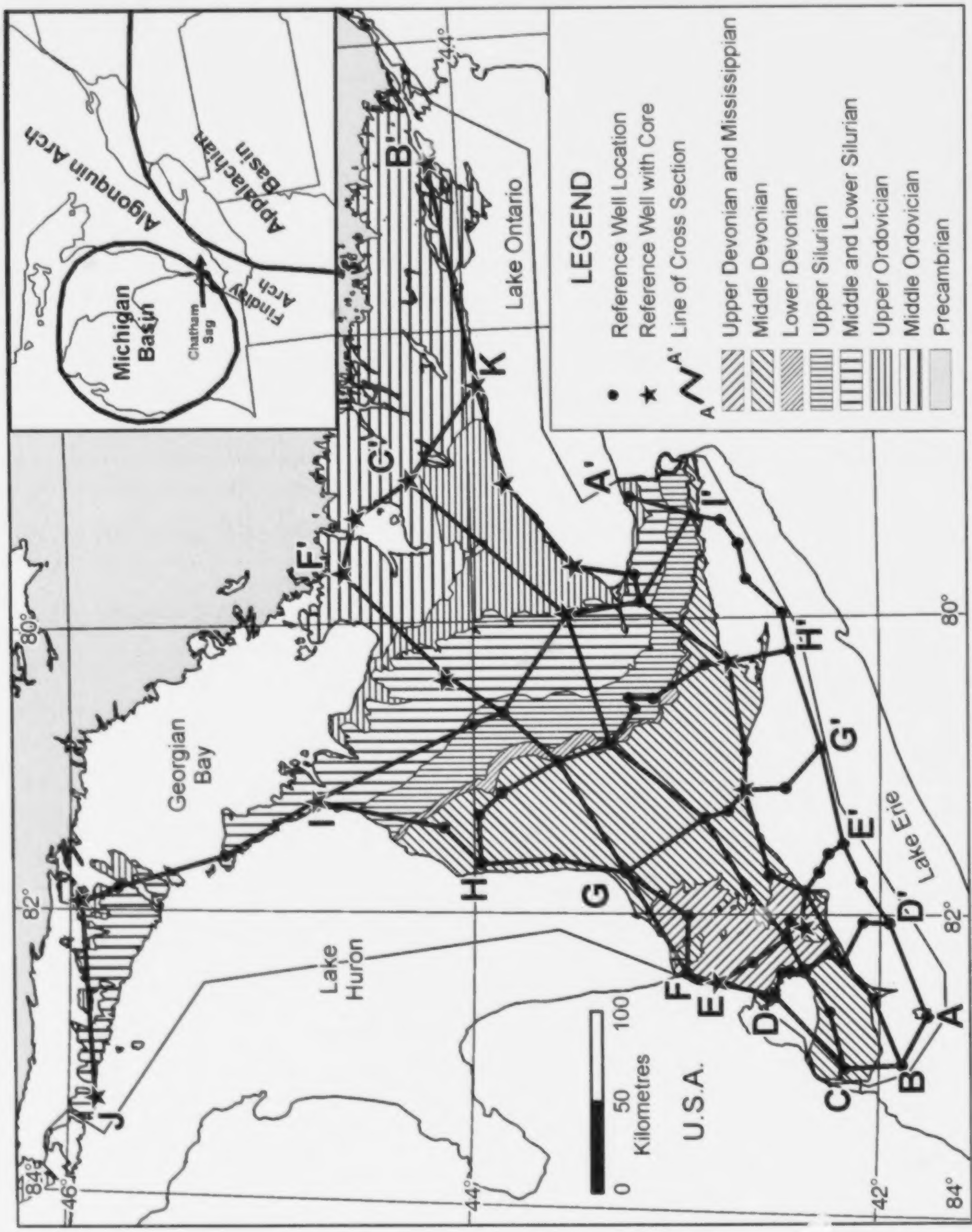
LEGEND
● Reference Well Location
★ Reference Well with Core
A–A' Line of Cross Section
Upper Devonian and Mississippian
Middle Devonian
Lower Devonian
Upper Silurian
Middle and Lower Silurian
Upper Ordovician
Middle Ordovician
Precambrian
Michigan Basin
Chatham Sag
Findlay Arch
Algonquin Arch
Appalachian Basin
Lake Huron
Georgian Bay
Lake Ontario
Lake Erie
U.S.A.
0 50 100
Kilometres
A A' B B' C C' D D' E E' F F' G G' H H' I I' J K
84° 82° 80°
46° 44° 42°

Figure 20.1. Generalized bedrock geology of southern Ontario, showing locations of reference wells and lines of section for this project (geology from Ontario Geological Survey 1991). Insert map shows major tectonic elements for this region.

Seventy-one wells have been selected as reference wells for this project. They are listed in Table 20.1 by cross-section line (note many wells are included in more than one line of section), and their locations are plotted in Figure 20.1. Sixteen of the reference wells were continuously cored; 14 of these by the OGS. Cored wells are highlighted in Figure 20.1 and Table 20.1.

Geophysical Logs

A key component of the project is the use of geophysical logs from the reference wells to define stratigraphic contacts and correlate formation top picks from well to well to construct the cross sections. With only a few exceptions, all reference wells have gamma-ray logs over the entire length of the well bore. Most wells also have neutron or density logs and recently drilled wells have photo-electric effect logs. Formation tops are picked by project staff on the gamma-ray logs using characteristic log expressions defined by Beards (1967) and/or as modified by project staff. The neutron and density logs identify zones of porosity and potential oil- and/or gas- and/or water-bearing intervals. The photo-electric effect logs are particularly useful for identification of dolomitized zones in the carbonate strata. These zones play a key role in formation of hydrocarbon traps in the subsurface. The logs are stored at the Oil, Gas and Salt Resources Library as hard-copy depth-correlated charts. Geophysical logs for each reference well are being scanned and digitized by OGSR staff using the software NeuraLog. This software will also be used to create the 12 regional cross sections.

Cores and Cuttings

Formation picks, based on geophysical logs, drill cuttings or core, are being made for each well. Core logging is being done by the author, whereas logging of cuttings is being done by M. Dorland (OGSR staff) under the supervision of T.R. Carter (MNR) and the author. At the time of writing, formation picks based on geophysical logs and cuttings have been made for 17 wells in southwestern Ontario (cross section lines C–A, D–D′, and parts of A–A′, B–B′, C–C′ and E–E′; see Figure 20.1). In addition, 3 cores have been logged: OGS-82-2 (T006045), U.S. Steel No. 1 (F005446) and OGS Bath No. 1 (F013651) (*see* Table 20.1).

Outcrops

A key component of this project is the correlation of units between the subsurface and surface outcrops. Reference outcrops for each unit were selected for this purpose from the literature and previous OGS mapping projects. Wherever possible, a unit's type section was used, however, proximity to a line of section was also considered a main selection criterion. A list of reference outcrop sections is presented in Table 20.2. In some cases, to document reported lateral variability, units may have more than one reference section.

Table 20.2 indicates progress made to date in measuring sections. All outcrops listed in the table are being visited, measured, described and sampled for this project. Exceptions may be made—due to time constraints—for outcrops previously described and sampled by the author. "Other sources" indicated in Table 20.2 include publications such as Brett et al. (2004), Tsujita, Tetreault and Jin (2001), Melchin et al. (1994), Cheel (1991), Derry Michener Booth and Wahl and OGS (1989), Telford and Johnson (1984), Winder and Sanford (1972), Liberty and Bolton (1971) and Liberty (1969).

Table 20.1. List of reference wells grouped into regional cross section lines. Well Licence #s are unique identifiers in the Petroleum Well Database. For locations of cross-section lines, *see* Figure 20.1. Wells with complete cores are indicated with an asterisk in the last column.

Well Licence #	Cross-Section Line	Well Name	Wells with Core
T008079	A–A′	Laker #1, Pelee 21-RP338	
T004772	A–A′	Consumers' 13501, L. Erie 313-N	
T006815	A–A′	Diamond Shamrock, L. Erie 240-V	
T004497	A–A′	Consumers' 13176, L. Erie 222-V-1	
T008512	A–A′	Pembina Central, L. Erie 185-M-3	
T005473	A–A′	Anschutz No. 4, L. Erie 128-Q	
T003011	A–A′	CPOG Haldimand No. 1, L. Erie 131-G	
T010044	A–A′	Talisman East, L.Erie 69-E-4	
T010043	A–A′	Talisman East, L.Erie 38-P-3	
T002887A	A–A′	CPOG Welland 2A, L. Erie 24-T	
T004907	A–A′	Bowman Dev., Wainfleet 7-4-III	
T002012	A–A′	Imperial Grantham 3-III	
T002843	B–B′	Amerada Hess Essex No. 2, Lake Erie 359-F	
T006539	B–B′	Consumers et al 33817, Mersea 3-13-A	
T007162	B–B′	Imperial Oil 646, Romney 31- Gore A	
T008230	B–B′	Pembina, Howard 1-96-BFC	
T010520	B–B′	GGOL Huron #1, Aldborough 4-C-VII	
T006078	B–B′	OGS 82-3, Yarmouth 3-9-I	
T010456	B–B′	TLM Disposal #1, Malahide 5-27-I	
F005446	B–B′	US Steel No.1, Charlotteville 21-I	*
T002048	B–B′	Imperial Oil, Glanford - 9 - III	
T002033	B–B′	Imperial Oil, Saltfleet 12-IV	
T006102	B–B′	OGS 83-2 Clarkson, Toronto 33-III	*
T006124	B–B′	OGS 83-3 Pickering 18-R3	*
F012058	B–B′	Arthur Gallagher Hope 25-II (with Jalore core)	
F013651	B–B′	OGS Bath No.1, S. Fredericksburg 18-I	*
T007191	C–C′	Pembina Maxus, Anderdon 2-II-V	
T008111	C–C′	PPC Rochester #15, Rochester 7-17-IV	
T007714	C–C′	PPC/Ram 22 Dover 2-1-VE	
T007395	C–C′	PPC Chatham 2-10-I	
T006960	C–C′	Hewitt Tundra et al, Mosa 8-21-II	
T001536	C–C′	IOE Bluewater et al, Delaware 15-III	
T009793	C–C′	Shiningbank/ JEL #82, South Easthope 1-22-V	
T006120	C–C′	OGS 83-I Halton, Nassagaweya 9-VII	*
T007726	C–C′	OGS 91-I, Brock 19-VIII	*
T007191	C–A	Pembina Maxus Anderdon 2-II-V	
T002843	C–A	Amerada Hess Essex No.2 Lake Erie 359-F	
T008079	C–A	Laker #1, Pelee 21-RP 338	

Table 20.1. continued.

Well Licence #	Cross-Section Line	Well Name	Wells with Core
T003071	D–D'	Camac Maverick Walpole No.1, Sombra 241-BK	
T006621	D–D'	PPC #4 Dover 8-14-XIIIE	
T006391	D–D'	Peregrine et al Dover 2-II-IXE	
T007714	D–D'	PPC/Ram 22 Dover 2-I-VE	
T006912	D–D'	Consumers' 34025, Tilbury East 1-5-NMR	
T007162	D–D'	Imperial Oil 646 Romney 31-Gore A	
T004754	D–D'	Consumers' 13502 Lake Erie 284-C	
T004772	D–D'	Consumers' 13501 Lake Erie 313-N	
T006044	E–E'	OGS 82-1 Moore 18-FC	*
T006965	E–E'	Ram #90 Sombra 8-20-V	
T007395	E–E'	PPC Chatham 2-10-II	
T007939	E–E'	Newstar 92-I Harwich 2-19-VI	
T006045	E–E'	OGS 82-2 Harwich 25-II ECR	*
T008230	E–E'	Pembina Howard 1-96-BFC	
T006814	E–E'	Diamond Shamrock Lake Erie 175-H-3	
T004567	E–E'	Consumers 13470 Lake Erie 176-U	
T004497	E–E'	Consumers 13176 Lake Erie 222-V-I	
T008556	F–F'	Imperial Brine Disposal #1, Sarnia 2-II-IVRSIR	
T007511	F–F'	Telesis et al 34600, Plympton 3-30-II	
T004105	F–F'	Firebird No.2, Stephen 1-3-XXI	
T004985	F–F'	Petromark et al, Elma 2-36-XIV	
T002713	F–F'	Buxton Bozlan No.1, Arthur 8-25-V	
H000015	F–F'	OGS Deep Hole #1 Corbetton, Melancthon 251-II	*
T007979	F–F'	OGS 93-5, Medonte 8-13-IX	*
T004105	G–G'	Firebird No.2, Stephen 1-3-XXI	
T001536	G–G'	IOE Bluewater et al, Delaware 15-III	
T006878	G–G'	Denison #1, Southwold 1-27-NSTREB	
T006078	G–G'	OGS 82-3, Yarmouth 3-9-I	*
T006818	G–G'	Diamond Shamrock Lake Erie 117-G	
T008512	G–G'	Pembina Central Lake Erie 185-M-3	
T007544	H–H'	BPI, Ashfield 2-6-XWD	
T004881	H–H'	Pacific, Culross 4-25-V	
T004767	H–H'	Pacific, Turnberry 1-1-II	
T004985	H–H'	Petromark et al, Elma 2-36-XIV	
T009793	H–H'	Shiningbank/JEL # 82 South Easthope 1-22-V	
T008974	H–H'	Cambright #80, Blenheim 3-10-VI	
T008102	H–H'	DGC Blenheim 7-21-V	
T007844	H–H'	Brett et al Burford 5-17-IV	
T001021	H–H'	Lloyd Vanderburg No.6 Windham I-XIII	
F005446	H–H'	US Steel No.1 Charlotteville 21-I	*
T005473	H–H'	Anschutz No.4 Lake Erie 128-Q	

Table 20.1. continued.

Well Licence #	Cross-Section Line	Well Name	Wells with Core
T006056	I–I′	OGS 82-4 Wiarton, Albemarle 4-25-I	*
T002613	I–I′	Monray No.1, Egrement 4-VI	
T002713	I–I′	Buxton Bozlan No. 1, Arthur 8-25-V	
T006120	I–I′	OGS 83-1 Halton, Nassagaweya 9-VII	*
T002048	I–I′	Imperial Oil, Glanford - 9 - III	
T004907	I–I′	Bowman Dev., Wainfleet 7-4-III	
T006883	J–C	OGS 85-7, Cockburn Island 16-II	*
T006305	J–C	OGS-83-5 Manitoulin Howland 6 - V	*
T002327	J–C	Thomas Wright No. 1, Assignack 48-I	
F012155	J–C	Imperial Oil No. 528, St. Edmund 44-I EBR	
T006056	J–C	OGS 82-4 Wiarton, Albemarle 4-25-I	*
T004854	J–C	Pacific, Greenock 1-32-VIII	
T007544	J–C	BPI, Ashfield 2-6-XWD	
T006364	J–C	Tipperary No. 4, Goderich 2-37-IX	
T004105	J–C	Firebird No.2, Stephen 1-3-XXI	
T008556	J–C	Imperial Brine Disposal #1, Sarnia 2-II-IVRSIR	
T006044	J–C	OGS 82-1 Moore 18-FC	*
T003071	J–C	Camac Maverick Walpole No.1, Sombra 241-BK	
T007191	J–C	Pembina Maxus, Anderdon 2-II-V	
T007979	F′–K	OGS 93-5, Medonte 8-13-IX	*
T007968	F′–K	OGS 93-4, Mara 6-21-VII	*
T007726	F′–K	OGS 91-1, Brock 19-VIII	*
F012058	F′–K	Arthur Gallagher Hope 25-II (with Jalore Mining core)	*

Table 20.2. Preliminary list of reference outcrops selected for this project, grouped by age. Status of outcrop description is indicated by "x" in one or more of last 3 columns.

Outcrop Location(s)	**Stratigraphic Unit(s) (Gp = Group, Fm=Formation, Mb =Member)**	**Outcrop described in**		
		this study	**previous OGS study**	**other source**
DEVONIAN				
Kettle Point, Lake Huron	Kettle Point Fm			x
Rock Glen Conservation Area (Arkona)	Hamilton Group: Widder Fm, Hungry Hollow Fm, Arkona Fm	x		x
Thedford Tile Quarry (Thedford)	Hamilton Group: Hungry Hollow Fm, Arkona Fm	x		x
Norfolk Quarry (Port Dover)	Dundee Fm			x
St. Marys Quarry (St. Marys)	Dundee Fm; Detroit River Gp: Lucas Fm	x		x
Maitland River (Goderich) and Formosa Reef	Dundee Fm; Detroit River Gp			x
Woodstock Quarry	Detroit River Gp: Lucas Fm, Amherstburg Fm	x		x
Beachville Quarry	Detroit River Gp: Lucas Fm	x		x
MacGregor-General Chemical Quarry (Windsor)	Detroit River Gp: Lucas Fm			x
Amherstburg Quarry	Detroit River Gp: Lucas Fm, Amherstburg Fm			x
Ridgemont Quarry	Onondaga Fm; Bois Blanc Fm; Bertie Fm (Silurian)	x		x
Cayuga Quarry	Bois Blanc Fm; Oriskany Fm; Bass Islands Fm (Silurian); Bertie Fm (Silurian)	x		x
SILURIAN				
Walkerton area and Saugeen River	Bass Islands Fm			x
Welland Tunnel	Salina Fm	x		
South Saugeen River	Salina Fm			x
Dolime Quarry (Guelph)	Guelph Fm; Eramosa Mb			x
Elora Gorge and quarry	Guelph Fm			x
Reformatory Quarry (Guelph)	Guelph Fm; Eramosa Mb			x
Rockwood Conservation area	Eramosa Mb; Amabel Fm			x
Dundas Quarry	Guelph Fm; Eramosa Mb			x
Vinemount Quarry	Lockport Fm: Eramosa Mb, Vinemount Shale, Goat Island Mb			x
Dufferin Quarry (Milton)	Amabel Fm			x
Niagara Gorge	Lockport Fm: Goat Island Mb, Gasport Mb; Decew Fm; Rochester Fm; Irondequoit Fm; Neahga Fm; Reynales Fm; Thorold Fm; Grimsby Fm; Cabot Head Fm; Whirlpool Fm; Queenston Fm (Ordovician)			x

Table 20.2. continued.

Outcrop Location(s)	Stratigraphic Unit(s) (Gp = Group, Fm=Formation, Mb =Member)	Outcrop described in		
		this study	previous OGS study	other source
SILURIAN, continued				
Highway 403 road cut	Guelph Fm?; Lockport Fm: Goat Island Mb, Gasport Mb; Rochester Fm; Irondequoit Fm; Reynales Fm; Thorold Fm; Grimsby Fm; Cabot Head Fm; Manitoulin Fm; Whirlpool Fm; Queenston Fm (Ordovician)			x
Jolley Cut (Hamilton)	Manitoulin Fm; Whirlpool Fm.			x
Bruce Peninsula - north shore and area outcrops	Guelph Fm		x	
Wiarton Quarry (Bruce Peninsula)	Eramosa Mb		x	
Wiarton road cut	Eramosa Mb; Amabel Fm		x	x
New England road cut (Manitoulin Island)	Fossil Hill Fm			x
Rocky Bay Bruce Pen.	Fossil Hill Fm; St. Edmund Fm; Wingfield Fm; Dyer Bay Fm; Cabot Head Fm.		x	x
Cabot Head (Bruce Peninsula)	Manitoulin Fm; Queenston Fm (Ordovician)		x	x
Lions Head (Bruce Peninsula)	Fossil Hill Fm		x	x
Georgetown area quarries	Whirlpool Fm			x
ORDOVICIAN				
Burlington-Milton-Mississauga area quarries	Queenston Fm		x	
East Meaford Creek	Georgian Bay Fm		x	x
Clay Cliffs, (Meaford)	Blue Mountain Fm		x	x
Craigleith (Collingwood)	Lindsay Fm: Collingwood Mb			x
Bowmanville Quarry	Lindsay Fm: Collingwood Mb, lower mb			x
Lindsay north road cut	Lindsay Fm		x	x
Picton Quarry	Lindsay Fm; Verulam Fm	x		x
Kirkfield south road cut	Verulam Fm: upper mb	x	x	
Gamebridge Quarry	Verulam Fm		x	x
Lafarge - Brechin Quarry (Brechin)	Bobcaygeon Fm	x	x	x
Coboconk road cut	Bobcaygeon Fm; Gull River Fm	x	x	x
Uhthoff Quarry (Orillia)	Bobcaygeon Fm; Gull River Fm		x	x
Shadow Lake road cut (Coboconk)	Shadow Lake Fm	x	x	x
Marmoraton Iron Mine (Marmora)	Gull River Fm; Shadow Lake Fm; Precambrian	x		x
CAMBRIAN				
Sloan Quarry (Joyceville)	Potsdam Gp	x		x

CONTINUING WORK

Field work will continue into the fall of 2004. Core and cuttings logging will also continue through the remainder of 2004. Cross sections will be constructed during the winter of 2005. The final report is due to be completed by March 31, 2005.

ACKNOWLEDGMENTS

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21. Project Unit 04-025. The Distribution and Source of Forest Ring-Related Methane in Northeastern Ontario

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INTRODUCTION

Forest rings are large, circular features identified in the boreal forests of Ontario and other regions of Ontario that are visible due to a change in vegetation around the edge of the ring. They are permanent features on the ground and were observed by geologists and foresters when airphotos first became available about 50 years ago. They range in diameter from approximately 50 m to almost 2 km and usually form perfect circles. Numerous theories have been put forward as to their origin and anecdotes describe them being drilled by geologists, who thought they were kimberlites, or being identified for land use protection by biologists, who thought they were biological features. Indeed, the prevailing view until 1999 was that they occurred due to the radial growth of a tree-killing fungus. This and other biological theories were put to rest by Veillette and Giroux (1999), who demonstrated conclusively that they are geological features characterized by (1) a slight depression in the mineral soil around the rim of the ring, usually filled with peat; and (2) their occurrence only in terrain where a significant component of carbonate exists in the shallow soils. They also determined them to be post-depositional, static features that do not expand but develop *in situ*.

In 1998, the Ontario Geological Survey (OGS) began testing a theory in concert with the Geological Survey of Canada (GSC) that the rings were "electrochemical cells" or centres of negative redox charge. The initial results of that work (Hamilton, Veillette and Komarechka 1999; Veillette and Giroux 1999) provided strong evidence that the features are associated with low redox areas. The follow-up work involved drilling and installation of monitoring wells and quantified distinct negative redox anomalies at 2 ring sites (Hamilton 2000b; Hamilton and Cranston 2000; Hamilton and Cranston 2001).

One of the outcomes of the detailed ring investigation was the discovery that the source of negative redox charge at one of the rings was methane (CH_4) in shallow overburden. Since that work was completed, a very large number of rings have been identified in the James Bay Lowlands and in the areas to the south. It was speculated that a significant proportion of these rings may also be due to methane. Knowing the distribution of the rings, the proportion that are due to methane, and the source of the gas could be of interest from the point of view of energy exploration and other fields of study. Not only could the rings be indicating a deeper source of gas, but some are so large that they may, in themselves, be of interest as potential reservoirs.

An orientation survey was initiated to determine the approximate proportion of the rings that are methane-sourced and, in a preliminary way, the source of the methane. The study involved satellite-image reconnaissance in a large study area that straddles the Precambrian–Phanerozoic contact, which is also the approximate physiographic boundary of the James Bay Lowlands (Figure 21.1). The study area encompasses approximately 150 000 km^2.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.21-1 to 21-26.

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THEORY OF RING FORMATION

As mentioned, the rings are permanent geological features that do not grow larger. Other considerations (Veillette and Giroux 1999) include their association with carbonate-rich terrain; their near-perfect circularity; their occurrence in both thin and thick overburden; their tendency to be cut-off by major rivers, but not by minor streams; the fact that they are never cut off to less than half a circle; and that, when coalescing, one always "eats" into the other rather than forming Olympic-style interlocking rings. As discussed below, there are also profound geochemical changes that occur in soils in the rim of the circle.

Their circularity both identifies the presence of a phenomenon and sets certain constraints on what that process of ring formation might be. Due to the minimization of surface area, all force-fields in isotropic media will eventually take on a circular morphology at sufficient distance from the origin. Such forces include pressure (groundwater advection, sound, ocean waves, etc.), magnetism, electricity, diffusion, heat, gravity, electromagnetic radiation and even biological dispersion (bacteria, tree roots, fungus, etc.). Forces most likely to play a role in the formation of surficial geological features include pressure (groundwater advection), diffusion, and electricity. For any of these forces to cause the rings, the medium, that is, the glacial overburden, must be isotropic with respect to that force.

Similar geological units, such as glaciolacustrine clay, till or glaciofluvial sands, are defined mostly by their grain size and, therefore, are fairly isotropic in the horizontal direction with respect to permeability. Groundwater advection outward from a central point within a specific surficial geological unit could account for features with circular morphology. There are several reasons why this is unlikely in the case of forest rings.

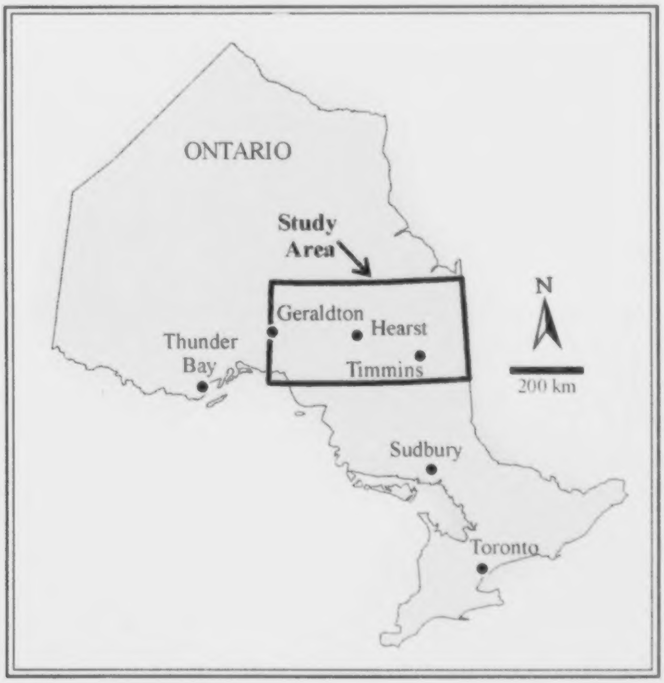

Figure 21.1. Location of study area within Ontario.

1. Transport by advection would be ongoing and, although it would form a circle, that circle would continue to expand until it reached a hydraulic boundary. The resulting static feature would not be round, but would be the shape of the surrounding boundaries.
2. Advection cannot by itself account for the physical depression and chemical changes that occur at the ring edges.
3. Rings could never form over areas where overburden or rock types have fundamentally different permeability and this is known to occur. An example is R10 ("Thorn-North", see below), a ring that is partly formed on clay and partly on esker sands, but which is nonetheless perfectly circular.
4. All rings would have to form in discharge zones, that is, all would be located in swamps, and although most rings are located in wet areas, many are not.
5. Discharge zones are not usually point-sources, but are large, irregularly shaped areas partly controlled by topography. There are no apparent topography-related patterns in the distribution of the rings that would suggest they occur exclusively in discharge areas.

Diffusion as a dispersion mechanism responsible for ring formation is even less likely.

1. Diffusion is very slow and cannot form features more than 10 or so metres larger than the source feature in the 8000 years since the last glacial deposits were laid down.
2. Diffusion is so slow that other dispersal mechanisms, such as groundwater advection, ought to dominate. In cases where permeability changes exist (as at Thorn-North), the drastically different advective flow rates would confuse any signal due to diffusion.
3. Diffusion is an ongoing kinetic process and cannot account for the sudden chemical and physical changes at the ring boundary.

Transport of ions in an electrical field can be very rapid and under certain circumstances could result in a circular morphology to the ion dispersion. For example, negative spontaneous potential anomalies measured above porphyry sulphide deposits are often roughly circular (Corry 1985). In addition, most saturated overburden materials in northern Ontario would have similar electrical conductivity because the salinity of groundwater is almost uniformly low. This would result in these media being fairly isotropic with respect to electrical fields. However, electrical fields could only be invoked if there is (1) a mechanism to produce them and (2) a related geochemical mechanism that causes chemical changes in the soils at a specific distance outward from a central point.

As part of a study to account for rapid metal transport to surface from buried mineral deposits, the OGS published a new electrochemical transport model (Hamilton 1998) that proposes redox gradients as a possible transport mechanism. It was argued that consumption of oxidizing agents in the overburden above a buried sulphide body or other reduced geological feature ought to result in propagation of the redox anomaly outward and upward away from the reduced feature. In time, this should result in the development of a "reduced chimney" between bedrock and the water table where an unlimited source of oxidizing agents exists. When the ring investigation first began in 1998, it was hypothesized that forest rings might also result from outward propagation of such a reduced chimney. As the area of the chimney increases, the available oxidizing agents around the outer perimeter would also increase. If the source of reducing agents is large enough and the medium is isotropic, this process would inevitably form a circle. Eventually, the increasing circumference of the circle would lead to a balancing of the availability of oxidizing agents with the source of reducing agents and the expansion would cease.

Although the size of the ring would cease to increase, the oxidation reactions would continue at the margins of the circle and their products and those of secondary reactions ought to accumulate. One of the more ubiquitous redox-active ions in glacial overburden is iron and one of the products of its oxidation from Fe^{2+} to Fe^{3+} is acid (H^+). It was proposed (Hamilton, Veillette and Komarechka 1999; Hamilton 2000a, 2000b) that the cause of the depression around the edge of the ring was removal of carbonate by acid produced by iron oxidation (Figure 21.2).

In 1998, the OGS and GSC carried out a brief investigation of several rings in northwestern Quebec and northeastern Ontario to test the hypothesis that the rings may be of electrochemical origin and that the carbonate depletion might be the cause of the depression on the ring edge. Among other things, it was determined that a carbonate depletion of up to 95% occurs in C-horizon soils at the edge of the rings as does an iron enrichment of up to 400% (Hamilton and Cranston 2000). This provide strong evidence for the process as described in Figure 21.2.

If redox-gradients are responsible for the development of circles, they would have to operate very quickly because the glacial deposits are less than 10 ka in age and the profound physical and chemical changes observed at the ring edge indicate they have been static for a long time. The Hamilton (1998) model argued that the element dispersion by redox-gradients would be very fast, but, at the time of that publication, there was no direct evidence that the process even occurred and theoretical support for it was

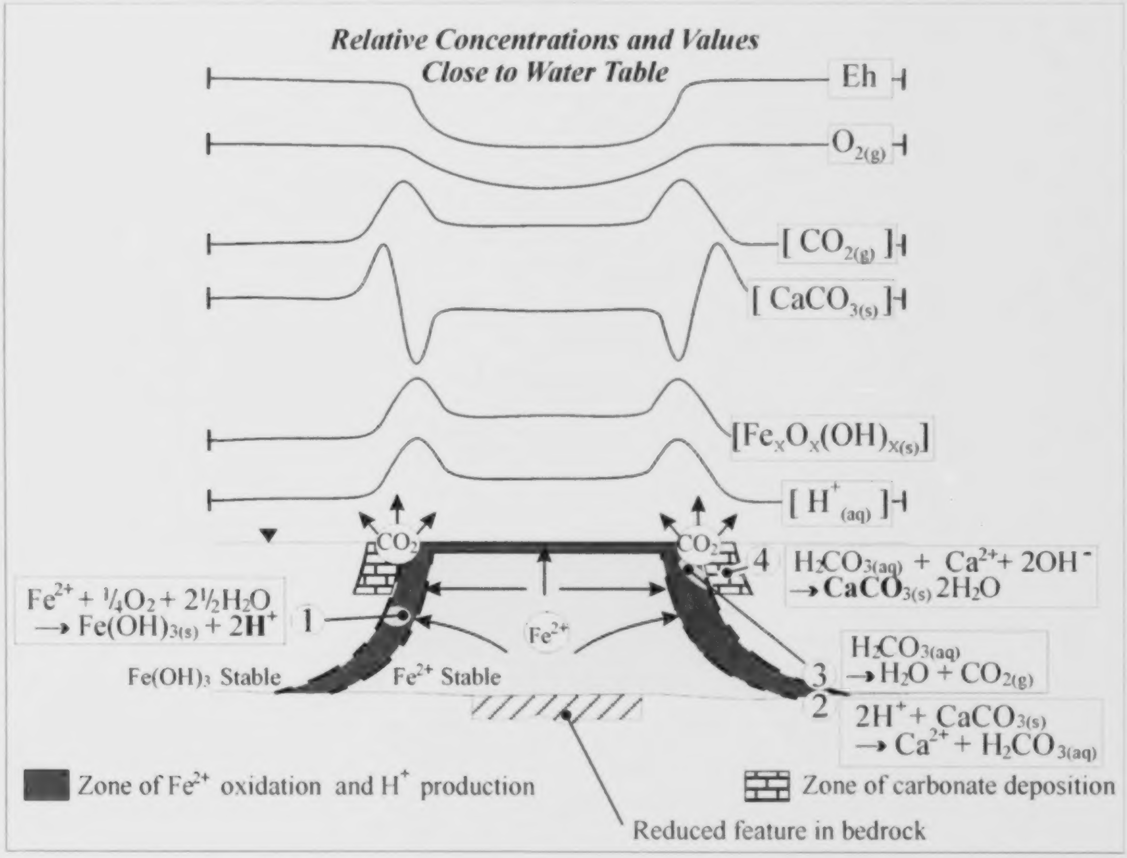
Relative Concentrations and Values Close to Water Table
Eh
$O_{2(g)}$
$[CO_{2(g)}]$
$[CaCO_{3(s)}]$
$[Fe_XO_X(OH)_{X(s)}]$
$[H^+_{(aq)}]$
CO_2
CO_2
4
$H_2CO_{3(aq)} + Ca^{2+} + 2OH^- \rightarrow CaCO_{3(s)} 2H_2O$
$Fe^{2+} + \frac{1}{4}O_2 + 2\frac{1}{2}H_2O \rightarrow Fe(OH)_{3(s)} + 2H^+$
1
Fe^{2+}
$H_2CO_{3(aq)} \rightarrow H_2O + CO_{2(g)}$
3
2
$2H^+ + CaCO_{3(s)} \rightarrow Ca^{2+} + H_2CO_{3(aq)}$
$Fe(OH)_3$ Stable
Fe^{2+} Stable
Zone of Fe^{2+} oxidation and H^+ production
Zone of carbonate deposition
Reduced feature in bedrock

Figure 21.2. The theory of ring formation. A reduced geological source such as sulphide minerals or methane maintains iron and other transitional metals in a reduced state within the ring. The oxidation of iron at the edge of the reduced area produces acid, which dissolves carbonate in soils and results in a depression. The products are elevated $CO_{2(g)}$ and iron in soil on the edges accompanied by depleted carbonate with flanking enrichments. The strong redox gradient at the edge of the ring is maintained by the migration of iron and other reduced species outward toward the more oxidized conditions at the edge of the ring.

weak, since the only indisputable dispersal mechanism for the reduced species was diffusion. Notwithstanding, subsequent investigation at the mineral deposit and ring sites demonstrated distinct redox anomalies and the predicted "reduced chimneys" associated with the features (Hamilton 2000b; Hamilton and Cranston 2000; Hamilton et al. 2004a, 2004b).

The existence of the predicted redox features suggests the dispersal mechanism is indeed very fast and that it is not simple diffusion. It is not the purpose of this paper to discuss in detail the theory of how this occurs, but it remains very similar to that advanced in Hamilton (1998). In short, it is argued that the redox gradient itself or a secondary electrical field established by the redox polarity, results directly in mass and charge transport. The results of this would appear similar to electricity, with large-scale voltage gradients (albeit redox voltage), mass and charge transport, and oxidation and reduction of ions, but there is no externally induced electrical field and no electrodes. As proposed, this represents a new mechanism for the movement of mass and charge. Evidence for it includes the very fast establishment of the reduced chimneys, the large-scale redox gradients, apparent mass transport, associated pH phenomena where oxidation is expected to occur (Hamilton et al. 2004a, 2004b; Cameron et al. 2004) and water table fluctuations at the edge of the reduced areas that appear to be due to some previously undocumented form of electro-osmosis.

The reduced geological materials that create the low-redox environment within the rings could conceivably be methane, bitumen, coal, sulphide mineralization, kimberlite or less interesting redox contrasts such as diabase intruded into granite country rock. The 2 rings investigated in detail—"Bean" (R0, below) and "Thorn-North" (R10, below)—are, respectively, methane- and hydrogen sulphide-sourced. A primary objective of this project is to gather enough evidence to determine roughly what proportion of the 1600 rings identified in the study area are methane-sourced.

RING DISTRIBUTION

In addition to the previously studied rings, ring locations were determined within the study area from 1) satellite-image reconnaissance by the OGS, which identified approximately 1600 ring locations; 2) 24 selected locations provided by Diatreme Explorations Inc. for a 2001 overflight of the rings; and 3) from a paper-file database of approximately 450 rings provided to the OGS by Diatreme Explorations Inc. The latter database was provided in confidence and will not be published, except where it coincidentally overlaps with the OGS database. A distribution map of rings across eastern Canada was published by Veillette and Giroux (1999), but it was of sufficiently small scale to not be of use in this investigation.

Figure 21.3 shows the OGS database with rings represented as proportional dots overlain on a Landsat satellite image of the study area. The dot size is exaggerated as shown in the legend to indicate the relative size and does not represent the actual surface area of each ring at the map scale. Areas that have been recently forested (i.e., in the last 30 years or so) as indicated by satellite image reconnaissance are shown in white. There are far fewer rings apparent in the logged area, which makes up about 22% of the study area, but accounts for only 3% of surface area of the rings. Most of these are actually located on small remnants of virgin forest within the larger logged areas that are too small to be accounted for at this scale. As a consequence, the forested areas have been excluded from the statistical assessment of ring distribution.

Notwithstanding the visual bias due to the forested areas, it is clear from Figure 21.3 there is a preponderance of rings in the northern half of the study area. Their distribution appears to be related to both Quaternary cover and the Precambrian–Phanerozoic boundary. Phanerozoic rocks cover 23% of the study area, but underlie 48% (by surface area) of the rings, meaning that rings are more than twice as likely to occur over Phanerozoic rocks as over the study area as a whole. Furthermore, the diameter of rings found over Phanerozoic rocks is considerably greater (Figure 21.4). The median diameter of rings over the Phanerozoic rocks is 390 m and the 98th percentile is 1325 m in contrast to 132 and 879 m, respectively, over the Precambrian rocks.

The occurrence and size distribution of rings is even more strongly influenced by the nature of the Quaternary cover. Figure 21.5 shows the percent likelihood of a ring (by surface area) occurring in each of the different surficial units mapped in the region relative to the likelihood of it occurring in the study area as a whole. The glaciomarine and marine unit stands out as being 6 times more likely to have rings overlying it than the study area as a whole. Bedrock, fluvial, glaciofluvial and coarse-grained ice-contact deposits are much less likely to have overlying rings.

Figures 21.6 and 21.7 show the areal distribution of marine deposits, organics, glaciolacustrine deposits, and till with the rings of each respective unit superimposed. Forested areas are blanked out.

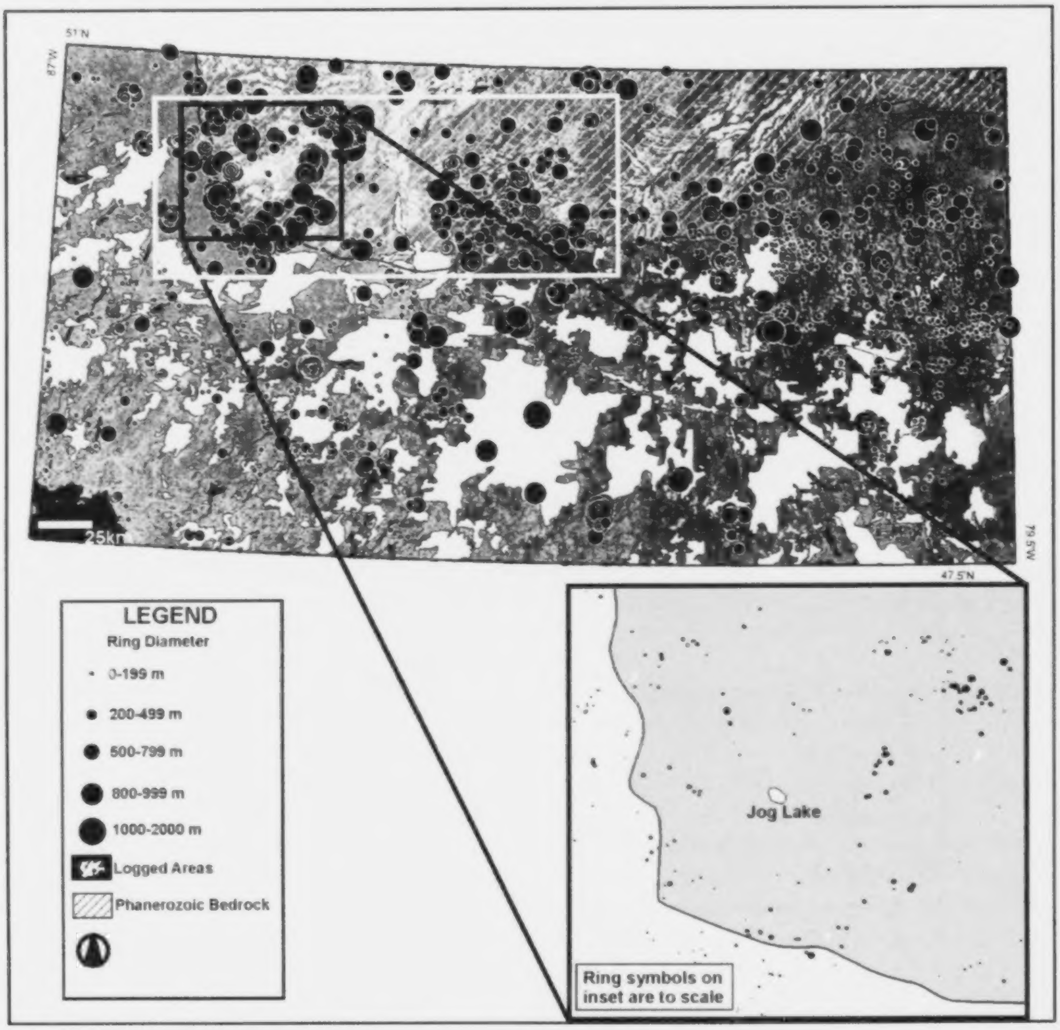
51°N
87°W
25km
79.5°W
47.5°N
LEGEND
Ring Diameter
0-199 m
200-499 m
500-799 m
800-999 m
1000-2000 m
Logged Areas
Phanerozoic Bedrock
Jog Lake
Ring symbols on inset are to scale

Figure 21.3. OGS satellite reconnaissance database of rings within the study area. Rings are overlain on a Landsat composite image with recently forested areas (i.e., last 30 or so years) in white. Note that rings sizes are as per the legend and are not to scale with respect to the image. Inset shows circular cluster of rings around Jog Lake to scale (area outlined in white is shown in Figure 21.8).

It can be seen that rings in the organics and marine deposits are typically larger than those of the clay deposits. The till unit tends to have even smaller rings, especially in the eastern third of the study area (*see* Figures 21.7 (top) and 21.3). The reason for this clustering of rings of under 200 m in diameter is not clear, but may be related to the hummocky nature of the terrain. Previous work indicates this cluster continues into western Quebec.

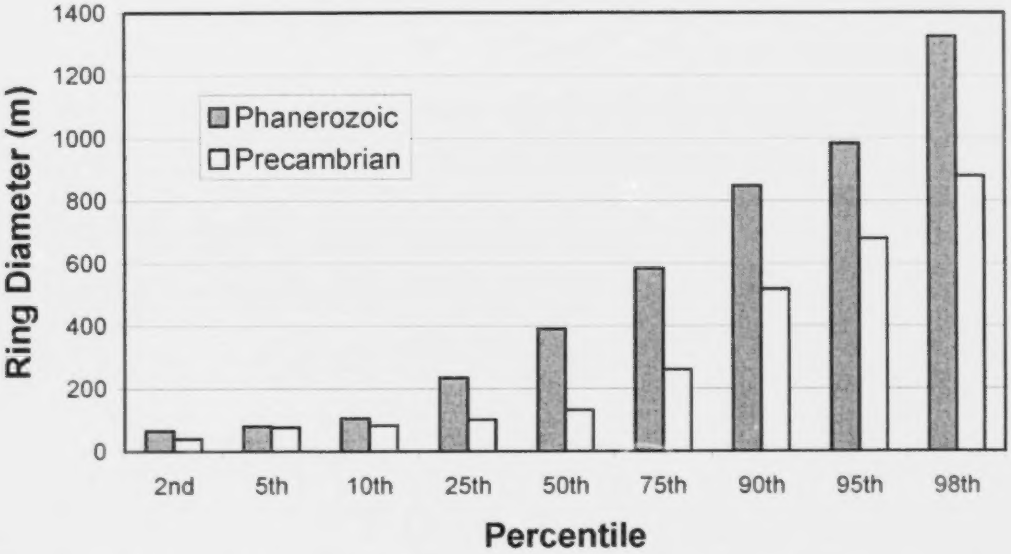

Figure 21.4. Percentile distribution of ring diameter for Precambrian and Phanerozoic rocks. Recently forested areas are excluded.

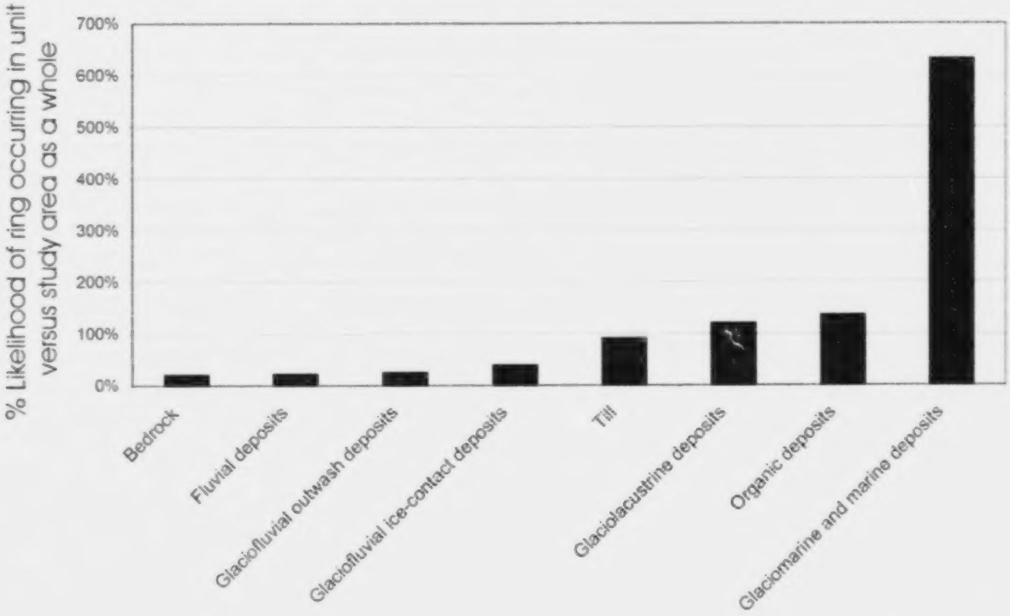

Figure 21.5. Percent likelihood (by surface area) of rings occurring in the 6 major Quaternary geological units mapped in the study area versus the likelihood of their occurring in the study area as a whole.

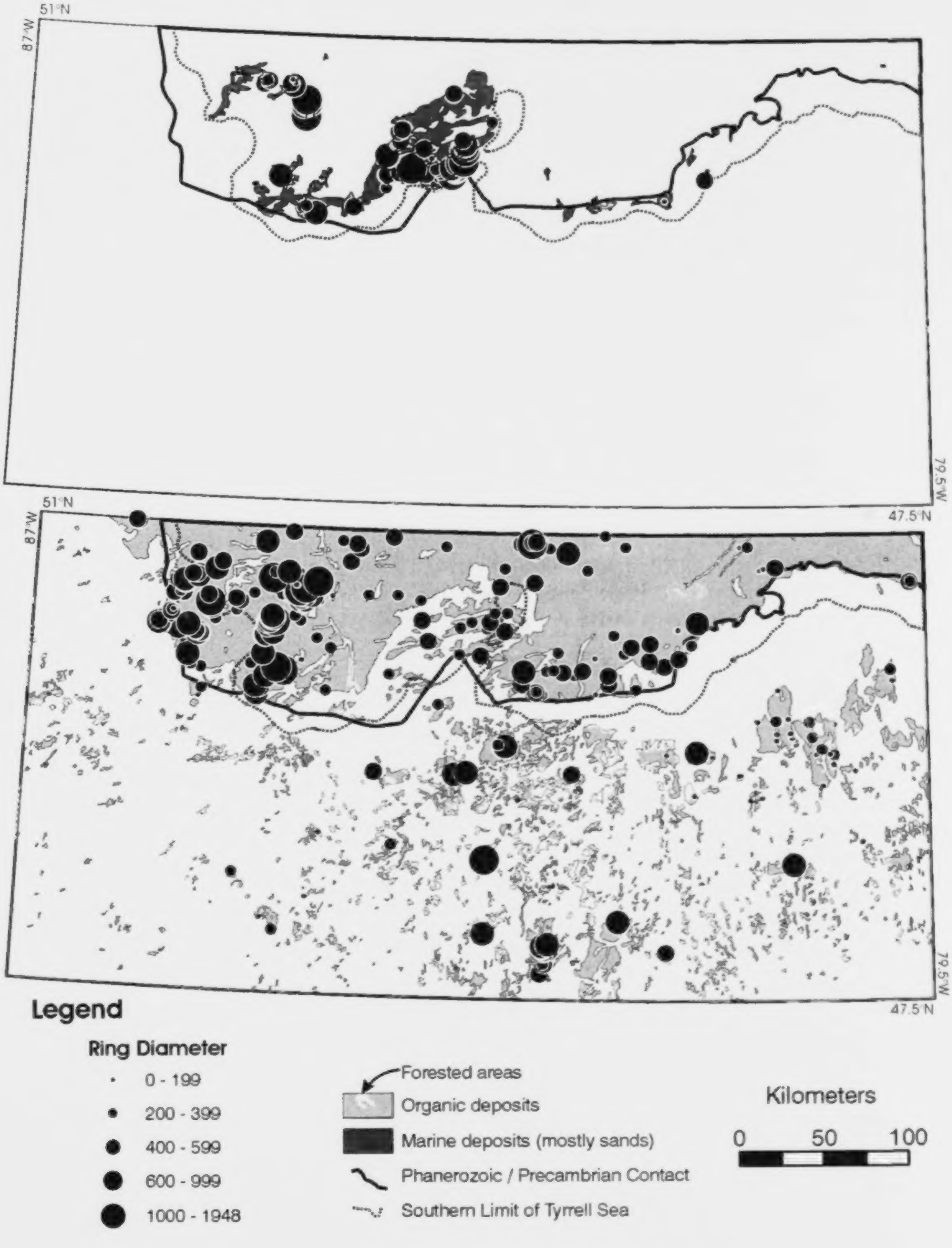
51°N
87°W
79.5°W
51°N
87°W
47.5°N
79.5°W
47.5°N
Legend
Ring Diameter
0 - 199
200 - 399
400 - 599
600 - 999
1000 - 1948
Forested areas
Organic deposits
Marine deposits (mostly sands)
Phanerozoic / Precambrian Contact
Southern Limit of Tyrrell Sea
Kilometers
0
50
100

Figure 21.6. The distribution of Pleistocene marine sands of the Tyrrell Sea (top) and Holocene organic deposits (bottom) with their overlying rings respectively superimposed.

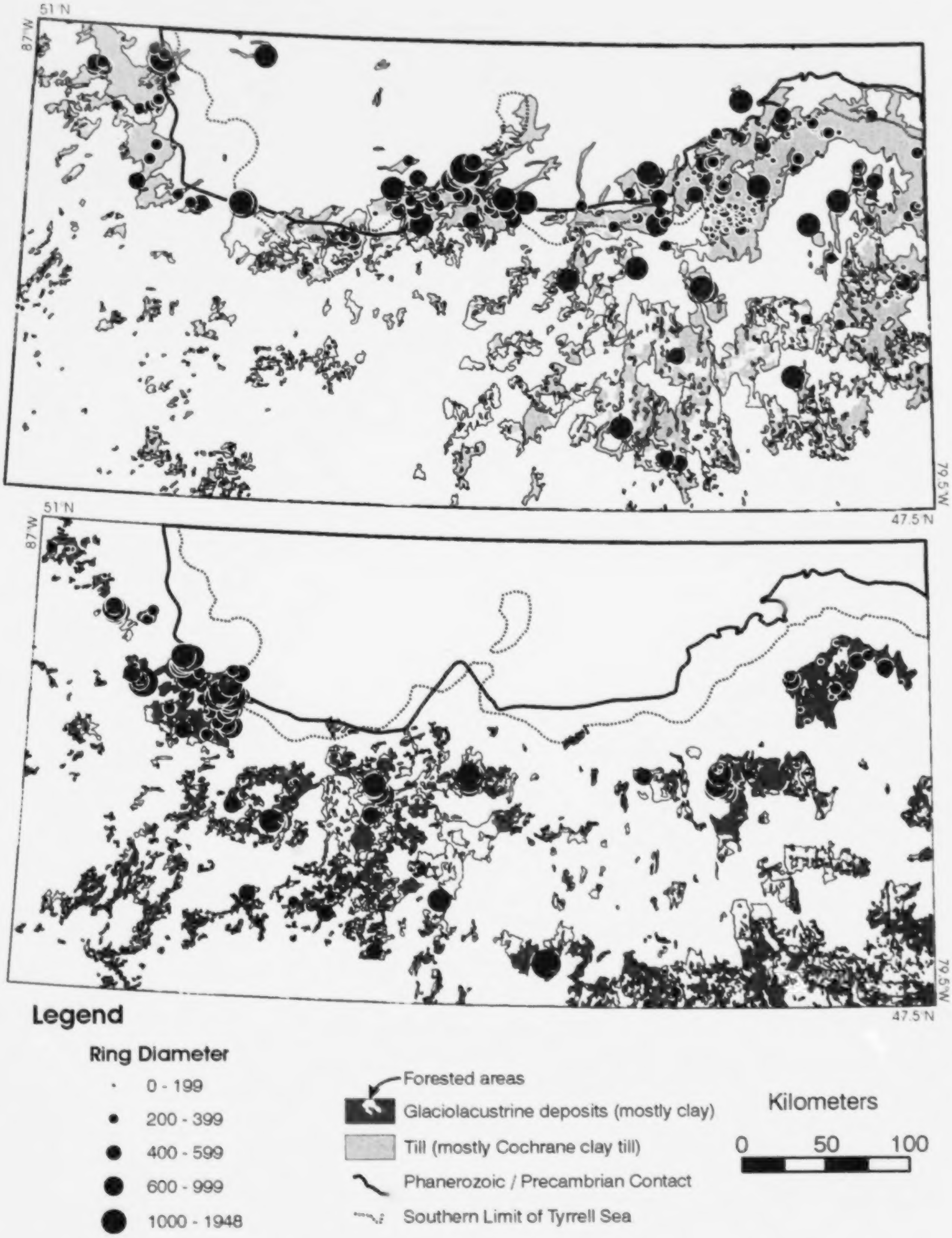
51°N
87°W
79.5°W
47.5°N
51°N
87°W
79.5°W
47.5°N
Legend
Ring Diameter
0 - 199
200 - 399
400 - 599
600 - 999
1000 - 1948
Forested areas
Glaciolacustrine deposits (mostly clay)
Till (mostly Cochrane clay till)
Phanerozoic / Precambrian Contact
Southern Limit of Tyrrell Sea
Kilometers
0
50
100

Figure 21.7. The distribution of Pleistocene glacial till (top) and glaciolacustrine deposits (bottom) with their overlying rings respectively superimposed.

The Tyrrell Sea boundary is shown on Figures 21.6 and 21.7. Despite the noted association between rings and marine sediments, the boundary does not seem to have as strong a control on the distribution of rings as does the Precambrian–Phanerozoic boundary (Figure 21.8). An interesting cluster of rings occurs at the southwest extremity of the Phanerozoic rock cover. It occurs as a circle of rings approximately 100 km across that is centred on Jog Lake, which is itself large and circular (*see* Figure 21.3, inset). Within this cluster, rings tend to increase in size toward the centre, to within 20 km of Jog Lake, and then they cease to occur. This may be due to a thickening of the organics and the appearance of string bog, which tends not to host rings. This, however, would not explain the radial pattern to some of the clusters, which are better accounted for by bedrock structural control of the ring distribution.

Methane Investigation: Methodology

The primary purpose of this study was to determine the proportion of rings that can be attributed to an underlying methane accumulation. A total of 11 rings of the approximate 1600 identified were chosen for testing. At all the rings investigated, forest cover required the cutting of lines, which ranged in length from 800 to 1100 m. Lines were cut from background areas outside of the ring across the ring edge and extending to at least the centre of the ring (Figure 21.9b). Pickets were placed at 50 m intervals along each line. At the estimated outermost edge of the ring, 2 large white flags were placed 10 m apart. The accuracy of the flag placements was checked from the air and adjusted if necessary prior to taking readings (*see* Figure 21.9b).

Three portable instruments were used for the measurement of methane: a hand-held flame ionization detector (FID), a photo ionization detector (PID) and a laser gas detector (spectral absorbance instrument). The FID is a small hand-held instrument with an internal pump that continuously draws gases into the instrument through a probe and hose extension. Hydrogen is used to ionize the sampled gas and the methane levels are measured by a charged electrical detector within the unit. The instrument was calibrated daily using 100 ppm methane. The FID was used to detect methane equivalent readings (0.1 to 50 000 ppm in 2 ranges) at 50 m intervals along the cut line as well as the middle of the ring edge.

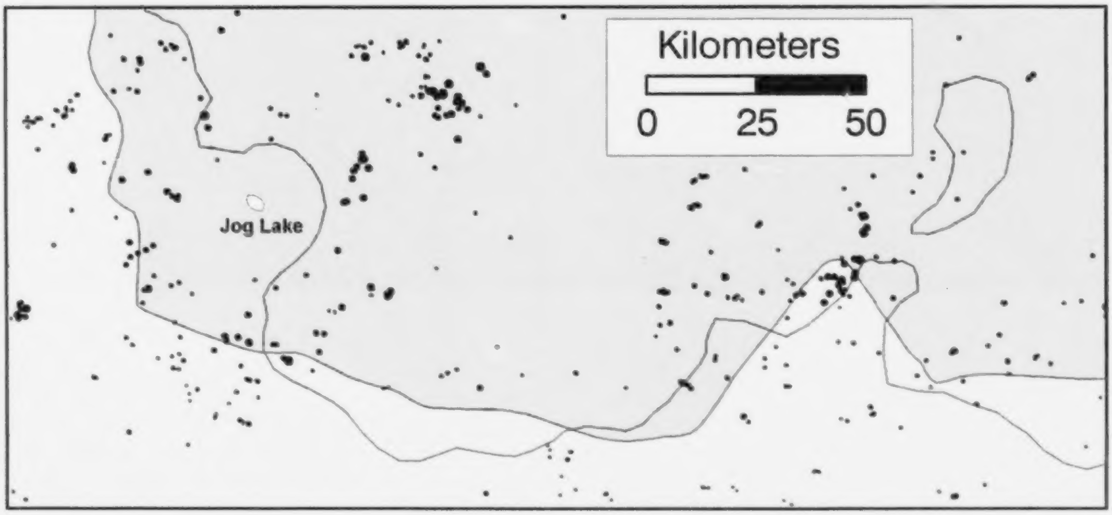

Figure 21.8. Extent of Phanerozoic rock shown in grey with the maximum southern extent of the Tyrrell Sea shown as a solid line. Rings are superimposed to scale. For location, *see* Figure 21.3.

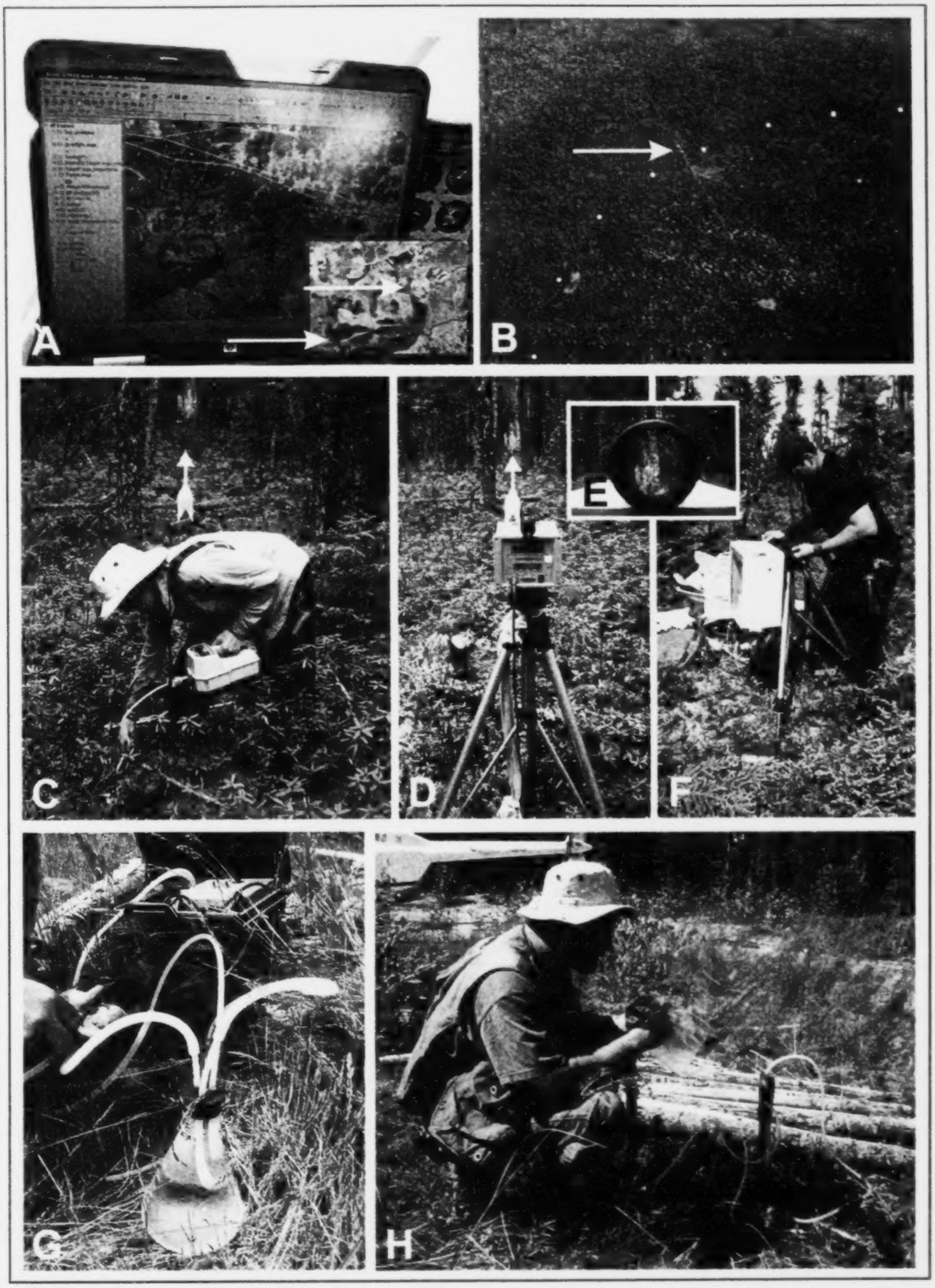

Figure 21.9. A) Real-time navigation using GPS and GIS. The locations of the target and helicopter (arrows on inset) are highlighted on screen during flight. B) Cut line and flags (arrow) at R7. The ring edge is highlighted by white dots. C) Measuring combustable gases, hydrocarbons and oxygen using the PID. The arrow indicates the direction of the cut line. D) Laser gas detector transceiver unit. E) Close-up view of aiming laser beam and cut line through the aiming scope. F) Laser gas detector remote reflector unit. G) Collecting gas sample from shallow monitoring well. H) Transferring gas sample to Tedlar® bag.

Two sampling methods were tested using the FID. In the first method, a 76 mm (3-inch) diameter Dutch auger was used to core to a depth of 1 m. The hole was plugged and the soils gases were allowed to accumulate for up to 2 hours prior to sampling. A clear flexible hose was inserted into the hole above the water table and the hole replugged so that the soil gases did not escape. Maximum soil gas methane equivalents were recorded. In the second method, a 25 mm (1-inch) diameter soil probe was used to auger sampling holes ranging from less than 0.5 m in sand and till to 1 m in peat. The flexible hose was immediately placed into the hole and the maximum methane equivalents recorded (Figure 21.9c). The 2 methods yielded similar results over a control line, but method 2 was much quicker, so it was adopted as the primary sampling protocol.

The PID was used to detect combustible gases (0 to 100% of the lower explosive limit (LEL) in 1% increments) hydrocarbons (0 to 10 000 ppm in 20 ppm increments) and oxygen (0 to 30.0% by volume in 0.1% increments) simultaneously at 50 m intervals along the cut line and the middle of the ring edge. Similarly to the FID, an internal pump continuously draws gases into the instrument through a hose and probe fitted with a hydrophobic filter. The combustible gas levels are measured using a catalytic compensated sensor and the oxygen using an electrochemical sensor. The instrument was only used during the latter few days in the project and was precalibrated prior to receiving it from the vendor. The instrument was zeroed in 'fresh air' prior to each use. Method 2, as described above, was used to obtain readings from a minimum of 2 holes at each sampling site.

The laser gas detector was a GasFinder 2.0 instrument rented from Boreal Laser Incorporated, located in Calgary, Alberta. It is an open path device and measures the cumulative total concentration (or average per-metre concentration) over long distances. A laser beam emitted from a transceiver unit is reflected off a remote reflector array back onto a photodiode detector within the transceiver. The resulting spectral absorbance is processed by the transceiver to determine the gas concentration. The instrument is calibrated for differences in reflected light levels and the distance between the transceiver and reflector array. The distance must be known precisely or erroneous concentrations will be displayed (http://www.boreal-laser.com).

The transceiver unit and remote reflector unit were set up outside the ring on a cut line at measured distances ranging from 150 to 250 m apart (Figures 21.9d, e and f). The actual distance depended on line-of-sight field conditions. The protocol used involved taking measurements inside the ring over the longest feasible distance and then again outside the ring at a roughly similar distance and comparing the ambient methane concentrations recorded in each set of readings. The instrument was repeatedly calibrated, 10 to 15 times, and readings were taken 1.5 minutes after each calibration. Prior to the beginning of each survey, the picketed distances between the laser and reflector was confirmed, and when necessary re-confirmed, using a filament-thread "hip chain".

Gas samples were obtained from 5 artesian wells at R0 (Bean ring) that had been drilled during the 1999 drilling program (Hamilton and Cranston 2000). Gas bubbles that came up with the flow were captured in an Erlenmeyer flask and transferred to a Tedlar® bag (Figures 21.9g and h). The samples were submitted to the University of Ottawa Isotope Laboratory for analysis of carbon isotopes.

The carbon isotope analytical procedure used was as follows. A septum was placed at the inlet of the sample bag under pressurized helium gas atmosphere. To minimize the contamination of atmospheric gas, the gas trapped between the septum and valve was removed using a syringe and filled with the sample gas by opening the metal valve. The sample gas was injected into the gas chromatograph (Hewlett-Packard 6890 with a column of 25 m × 0.32 mm filled with Poraplot Q) using a syringe. CH_4 was converted into CO_2 using Cu_2O at 960° C in a Finnigan™ GC Combustion III instrument. Isotopic compositions of the resultant CO_2 were measured with a Thermo Finnigan™ DELTA^{plus}XP mass spectrometer. The reference gas used for the calibration was –42.5‰ PDB (Peedee belemnite).

Site Descriptions

The 11 sites visited as part of this project are referred to as R0 to R10 and their locations are shown on Figure 21.10. One of the sites, R0, was previously known to be methane-sourced and another, R10, was known not to be. R10 has been determined from earlier work to be hydrogen-sulphide sourced with little or no methane present (OGS unpublished data). The origin of the other 9 rings was unknown, although one (R2) was strongly suspected to not be related to methane because of thin drift cover and outcrop within the ring.

Site R0 (Figure 21.11), also referred to as "Bean" ring was previously investigated (Hamilton and Cranston 2000) and determined to be methane-sourced. It has a diameter of about 480 m and is accessible to within 3 km by a summer access road. The laser GasFinder and FID were used on 3 lines located on orthogonal drill roads. Also located along these drill roads are a total of 21 shallow monitoring wells with screens at about 9 m depth. During earlier studies, groundwater was extracted from these wells and analyzed. As well, down-hole self-potential (SP) was carried out at each well. Most of the wells are artesian and a significant amount of methane (up to several litres per hour) is being discharged from the wells. Methane was collected from 4 wells and a gas sample taken from a deep well at the centre of the site that is finished in limestone bedrock. Samples were analyzed for carbon isotopes to determine the source of the methane and the results are discussed below.

The R0 ring is located in Cochrane Till, which locally contains lenses of sand. Overall overburden thickness at this site is 30 m. Underlying the overburden is Paleozoic limestone bedrock that is less than 50 m thick based on depth-estimation using magnetic data. It is presumed the methane is in vapour form in sand lenses within the till. Much less gas was noted in groundwater sourced from bedrock than from the shallow wells. Artesian conditions are more pronounced with increasing depth of overburden. The hydraulic head in the limestone bedrock was between 3.3 and 4 m above ground surface, whereas the highest recorded in the shallow overburden was only about 2 m. An unusual black-spruce aureole occurs beyond the light coloured rim of the ring (*see* Figure 21.11). Aureoles beyond the edge of rings have been noted in relatively few other cases. They suggest a large amount of chemical energy must be involved in the process of ring formation to cause such an extensive modification of the vegetative patterns beyond their edges. During soil sampling, ice in the peat was noted on 2 occasions in the centre of the ring at R0 and nowhere else inside or outside the ring.

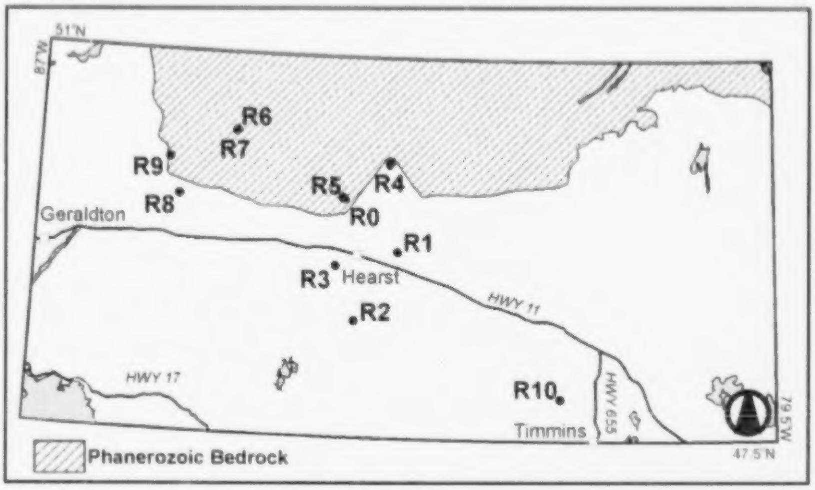

Figure 21.10. Forest ring sites visited as part of this study.

R1 (Figure 21.12) is a large ring, also referred to as the "Cheechka" ring with a diameter of 1.1 km. It is located in an area underlain by glaciolacustrine clay and Precambrian bedrock. Several rings occur nearby, some of which are located in areas that have been partially logged out. A very sudden and significant change in the size of trees occurs between the inside and outside of the ring at its edge. A 1 km line was cut into the centre of the rings and FID, PID and laser GasFinder surveys were carried out. While auguring in the centre of R1, ice was encountered in the peat.

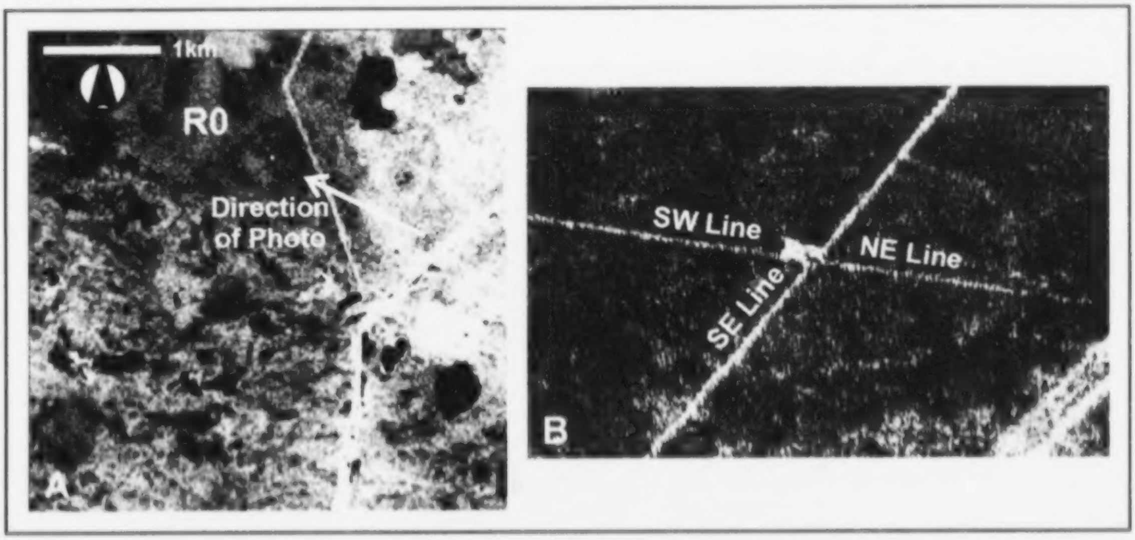

Figure 21.11. Site R0, the "Bean" ring, located 60 km northwest of Hearst, Ontario. "A" shows a Landsat satellite image and "B" an oblique airphoto taken during the winter 2000 drill program. Note the unusual aureole of black spruce around the ring, visible on both the air photo and the satellite image. Orthogonal lines are drill-roads and laser GasFinder surveys were carried out in the 3 that are labelled. The location of this ring was originally supplied to the OGS by Diatreme Explorations Inc.

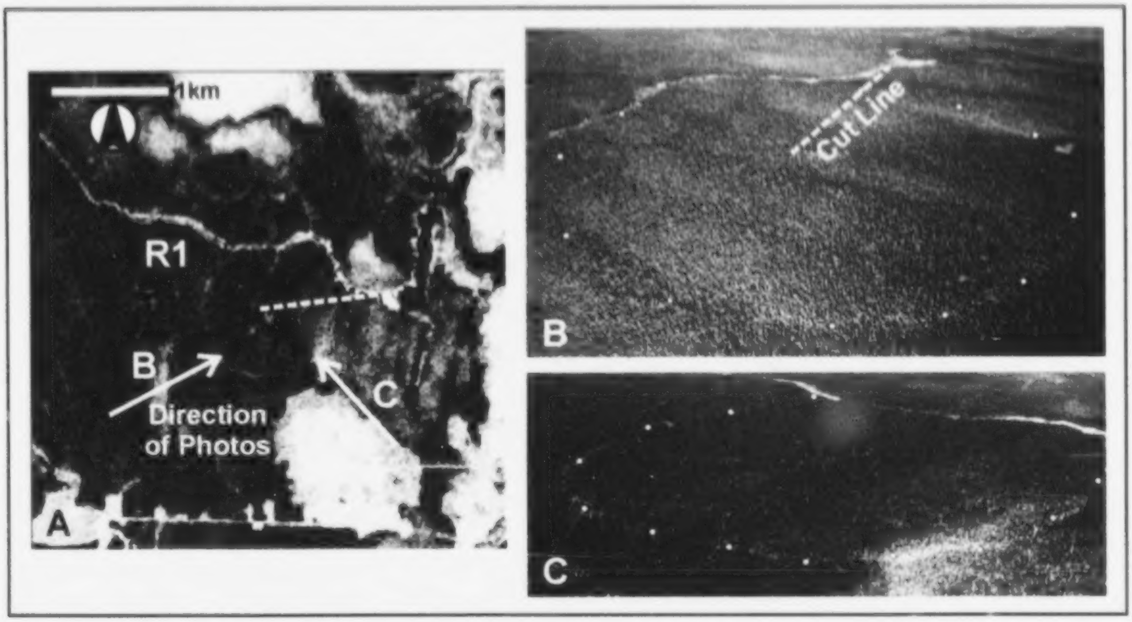

Figure 21.12. Site R1, the "Cheechka" ring, located 25 km east of Hearst. This large ring is visible in both summer (B) and winter (C). The satellite image (A) shows several other rings nearby. The location of this ring was originally supplied to the OGS by Diatreme Explorations Inc.

The R2 ring (Figure 21.13) is located in a thin-drift area underlain by Precambrian bedrock and is approximately 400 m in diameter. Because of the thin drift, it was assumed this ring was not methane-sourced. It was chosen for study as a probable example of a non-methane-sourced ring because of the thin drift and previously known bedrock outcrops. A 1 km line was cut to the centre of the ring and was measured with the laser GasFinder. Bedrock outcrop at the centre of the ring was determined to be diabase.

The R3 ring (Figure 21.14) is accessible via a logging road by all-terrain vehicle (ATV) and is 600 m in diameter. It occurs in an area of glaciolacustrine clay underlain by Precambrian bedrock. A laser GasFinder survey was carried out on the 750 m long cut line. Follow-up work with both the PID and FID was also carried out.

The R4 ring is 975 m in diameter and is one of a cluster of rings of almost exactly the same size (Figure 21.15) that overlie the Early Paleozoic Martison Carbonatite Complex. They also occur within the Quaternary glaciomarine sands and gravels that formed around the margin of the Tyrrell Sea and were discussed under "Ring Distribution" (above). Existing cut lines and drill

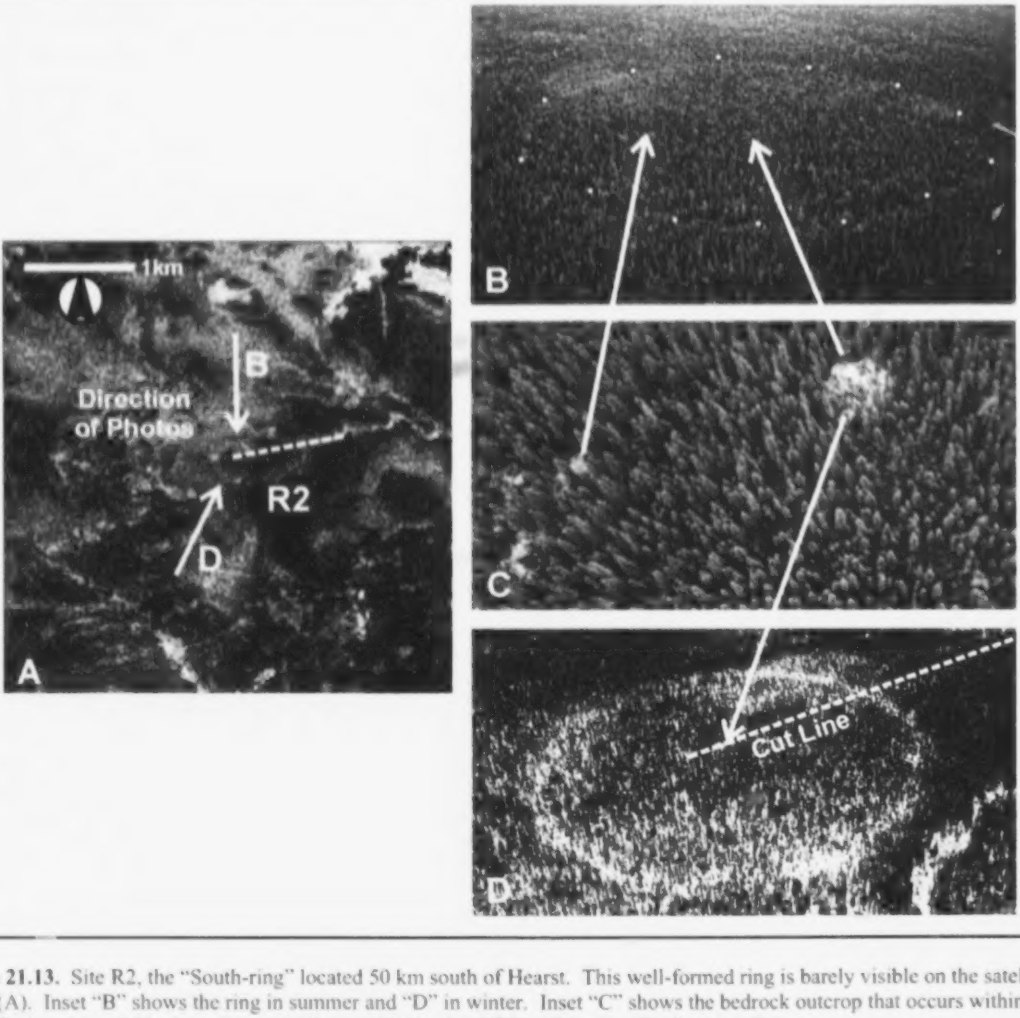

Figure 21.13. Site R2, the "South-ring" located 50 km south of Hearst. This well-formed ring is barely visible on the satellite image (A). Inset "B" shows the ring in summer and "D" in winter. Inset "C" shows the bedrock outcrop that occurs within the ring. The location of this ring was originally supplied to the OGS by Diatreme Explorations Inc.

roads completed during exploration drilling of the carbonatite were used as a helicopter landing site and as a survey line for the laser GasFinder. It may be possible in future to access other rings in this area using these lines.

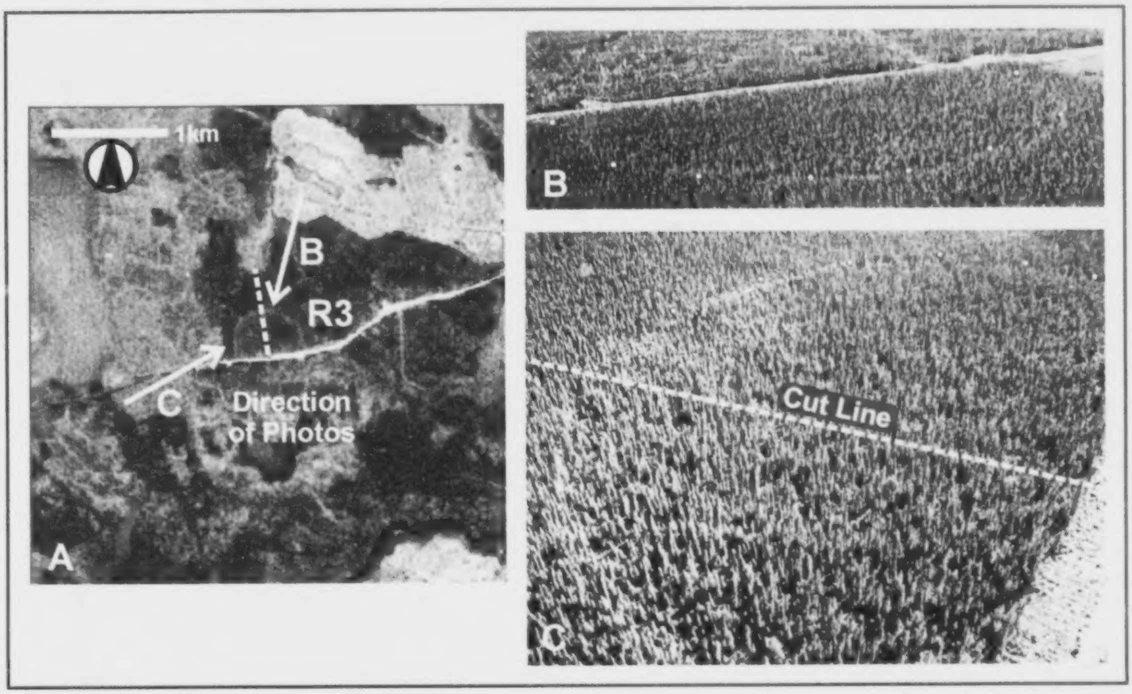
1km
B
R3
C
Direction of Photos
A
B
Cut Line
C

Figure 21.14. Site R3, the "Road-ring" located 20 km west-southwest of Hearst. This ring was chosen because it is road accessible. The satellite image (A) shows the active logging that is occurring to the northeast of the ring, suggesting it may soon be obliterated. Insets B and C show the outline of the ring (white dots) and sampled cut line, respectively.

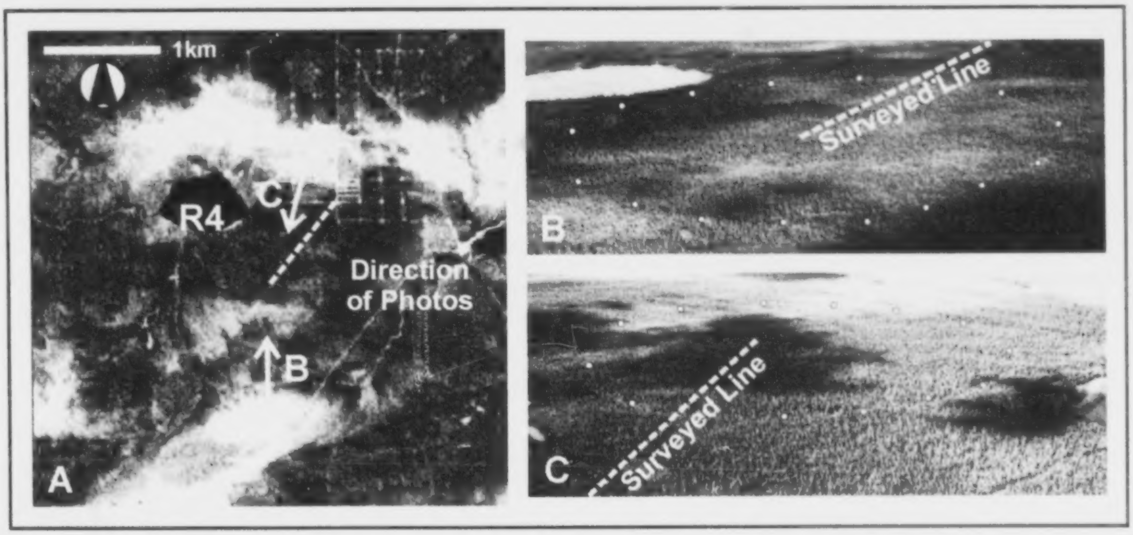
1km
R4
C
Direction of Photos
B
A
Surveyed Line
B
Surveyed Line
C

Figure 21.15. Site R4, overlying the Martison Carbonatite Complex, 75 km north of Hearst. The satellite image (A) shows at least 3 other large rings of approximately the same size that all overly the carbonatite. Insets B and C show the outline of the ring (white dots) and sampled cut line, respectively.

R5 is a ring currently staked by Diatreme Explorations Inc. and which they refer to as the "Eyeball" ring because of its appearance (Figure 21.16). It consists of a ring within a ring and is located 3 km west of R0 in similar overburden and bedrock terrain. An 800 m cut line was surveyed using the laser GasFinder.

R6 and R7 (Figure 21.17) were both accessed from the same helipad, which we were obliged to cut in a swamp since it was the only sparsely treed landing area within a large cluster of similarly sized rings. The cut lines on R6 and R7 were 650 and 1100 m long, respectively, and were surveyed using the laser

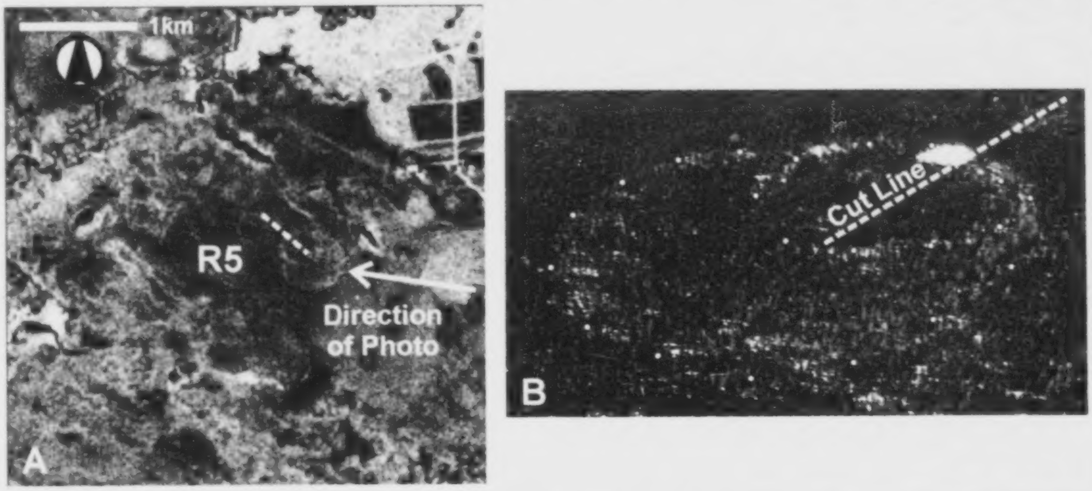

Figure 21.16. Site R5, the "Eyeball" ring, located 65 km northwest of Hearst, near R0. The ring is so named because the smaller ring encroaching upon the larger, visible on the satellite image (A), resembles an eye. The white area on the oblique airphoto (B) is snow on a helipad cut by Diatreme Explorations Inc., who originally provided the location of this ring.

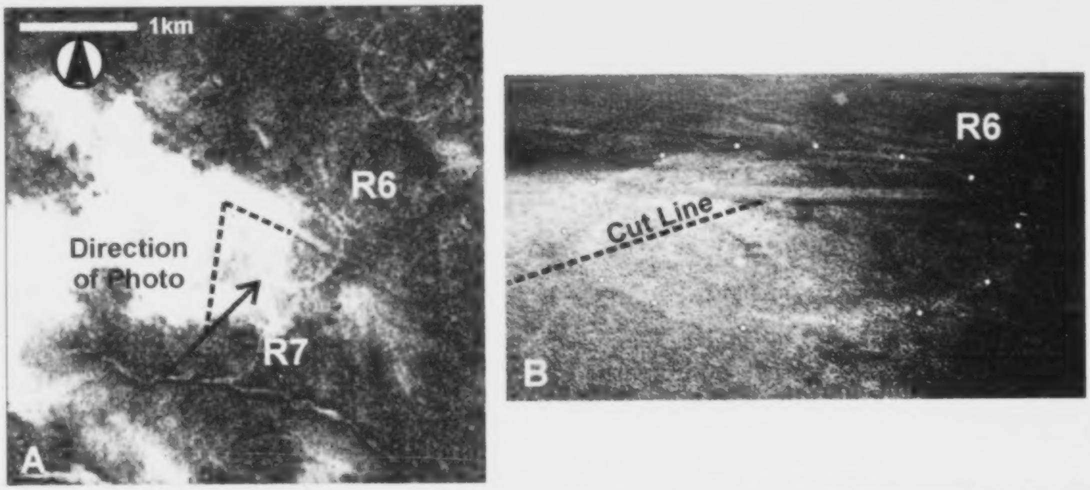

Figure 21.17. Sites R6 and R7, located 125 km east-northeast of Nakina, Ontario. One other well-formed ring (upper right corner) is visible on the satellite image (A). An iceberg grounding scar across R6 can be seen on both the satellite image and the oblique airphoto (B). R7 is not shown on the oblique image.

R5 is a ring currently staked by Diatreme Explorations Inc. and which they refer to as the "Eyeball" ring because of its appearance (Figure 21.16). It consists of a ring within a ring and is located 3 km west of R0 in similar overburden and bedrock terrain. An 800 m cut line was surveyed using the laser GasFinder.

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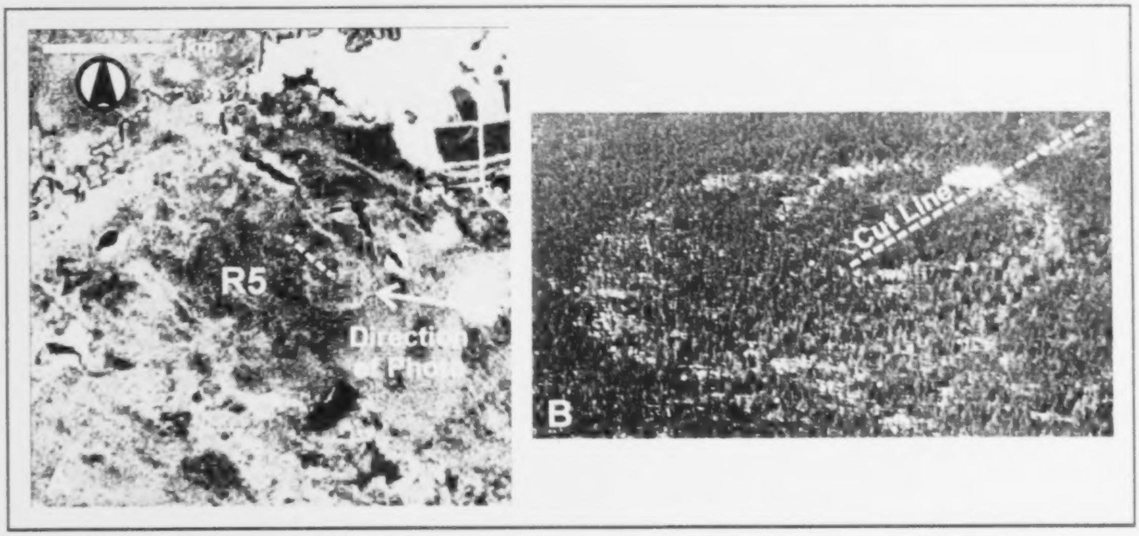

Figure 21.16. Site R5, the "Eyeball" ring, located 65 km northwest of Hearst, near R0. The ring is so named because the smaller ring encroaching upon the larger, visible on the satellite image (A), resembles an eye. The white area on the oblique airphoto (B) is snow on a helipad cut by Diatreme Explorations Inc., who originally provided the location of this ring.

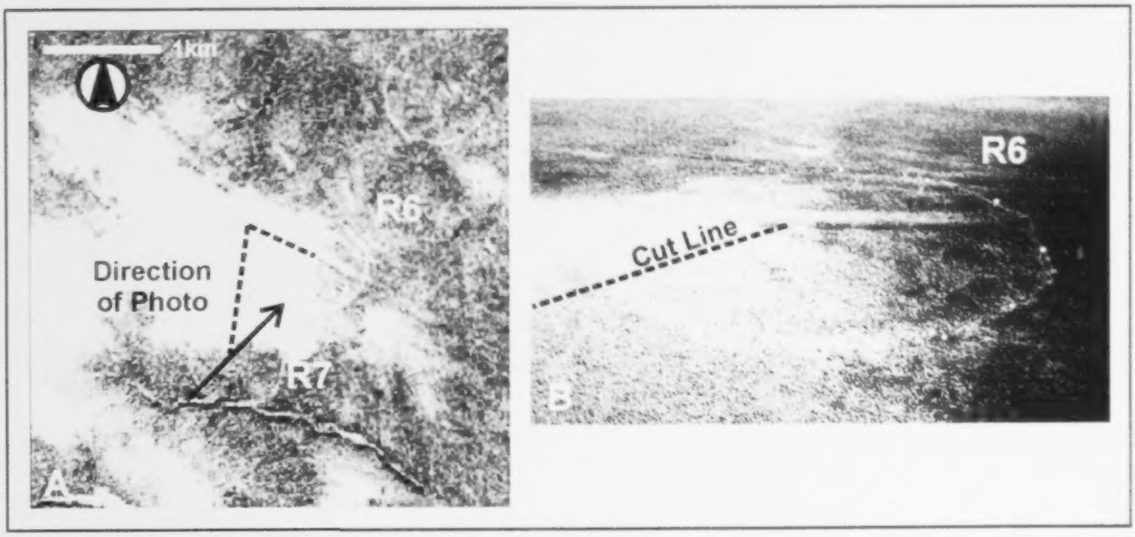

Figure 21.17. Sites R6 and R7, located 125 km east-northeast of Nakina, Ontario. One other well-formed ring (upper right corner) is visible on the satellite image (A). An iceberg grounding scar across R6 can be seen on both the satellite image and the oblique airphoto (B). R7 is not shown on the oblique image.

GasFinder. Both rings are about 850 m in diameter whereas most of their neighbours are slightly larger at just under 1 km across. These rings are well within the James Bay Lowlands in an area mapped as organic terrain, which is underlain by clay and then Paleozoic bedrock. The cluster is part of the large, 100 km wide circle of rings discussed under "Ring Distribution" (above).

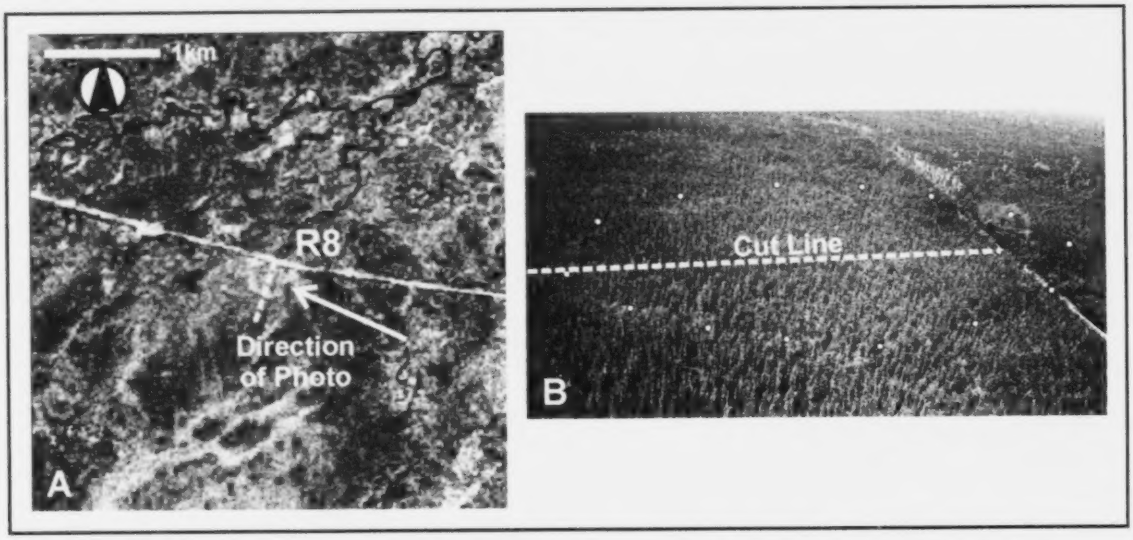

Figure 21.18. Site R8, the "rail-ring". This site is accessible by all-terrain vehicle along an abandoned rail line located approximately 110 km northeast of Geraldton, Ontario.

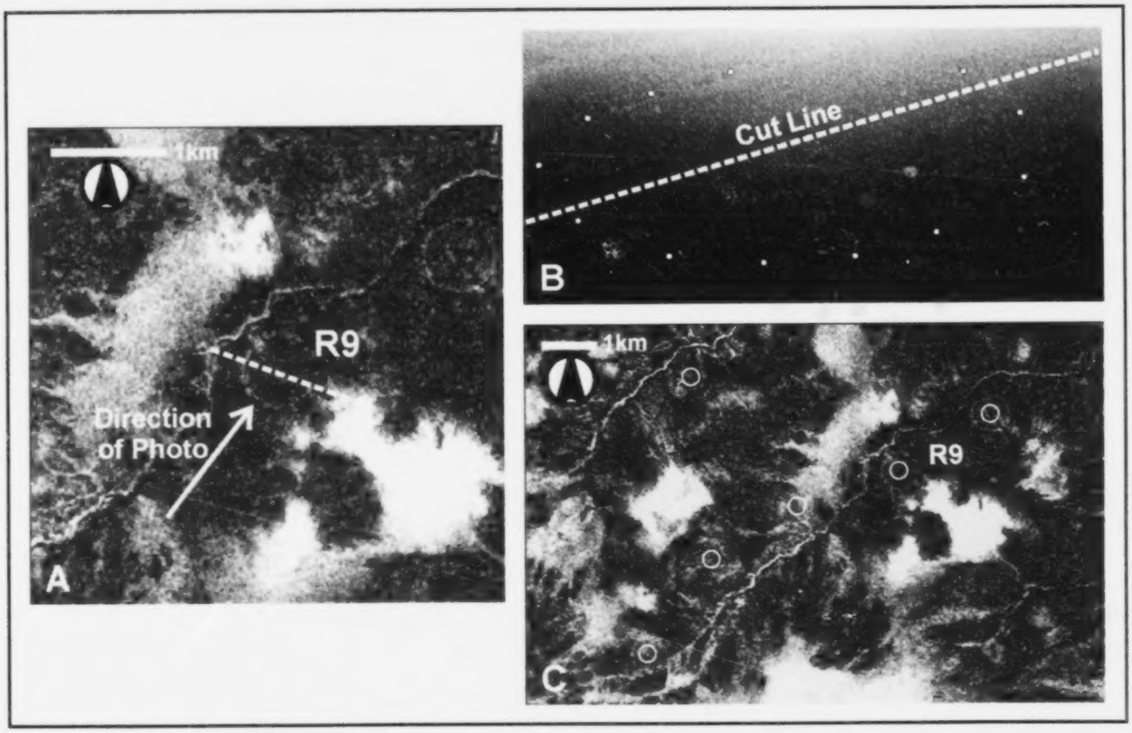

Figure 21.19. Site R9, located 80 km east of Nakina. An obvious line of equal sized rings are visible on the satellite images (A and C). R9 was chosen because it is located near a bog where helicopter landing was possible.

R8 (Figure 21.18) is accessible by ATV along an abandoned rail line. Its 350 m diameter makes it the smallest of the rings investigated as part of this study. A 650 m line was cut and a laser GasFinder survey carried out. The area is underlain by till and Precambrian bedrock.

R9 is one of an interesting cluster of rings that occur in an almost straight line along a lineament on the edge of the James Bay Lowlands (Figure 21.19). R9 is itself located 3 km east of the Precambrian contact and overlies Paleozoic rocks, but the lineament transects the contact and the southernmost 2 rings shown in Figure 21.19c overlie the Precambrian rocks. All the rings in this cluster are approximately the same size, ranging between about 625 and 675 m across. The Quaternary cover is mapped as glaciolacustrine clay. R9 was chosen because it was helicopter accessible from a swamp located to the southeast. A 1.4 km long line was cut right across the ring and laser GasFinder surveys were carried out across both the northwest and southeast edges of the ring.

R10 (Figure 21.20) was the second of 2 rings that were investigated in detail in 2000 and 2001 and is the only one included in the current study that is known to have a non-methane-source (its source is hydrogen sulphide). It is 550 m across and is located in an area of Precambrian greenstone overlain by about 30 m of glacial sediments. The overburden consists of glaciolacustrine clay on the western half and glaciofluvial on the eastern half of the ring. An esker is located to the immediate east. Two lines were tested using the laser GasFinder equipment.

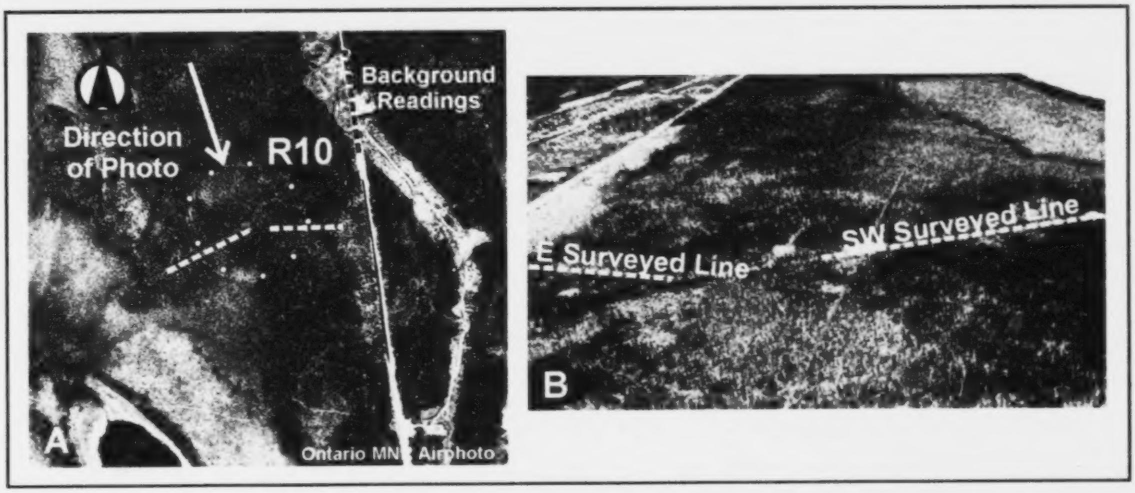

Figure 21.20. Site R10, the "Thorn-North" ring, located 45 km northwest of Timmins, Ontario. The lines visible on the oblique airphoto (B) are drill roads, the 2 of which are labelled were used for laser GasFinder surveys. The location of a background survey is also shown on the satellite image (A).

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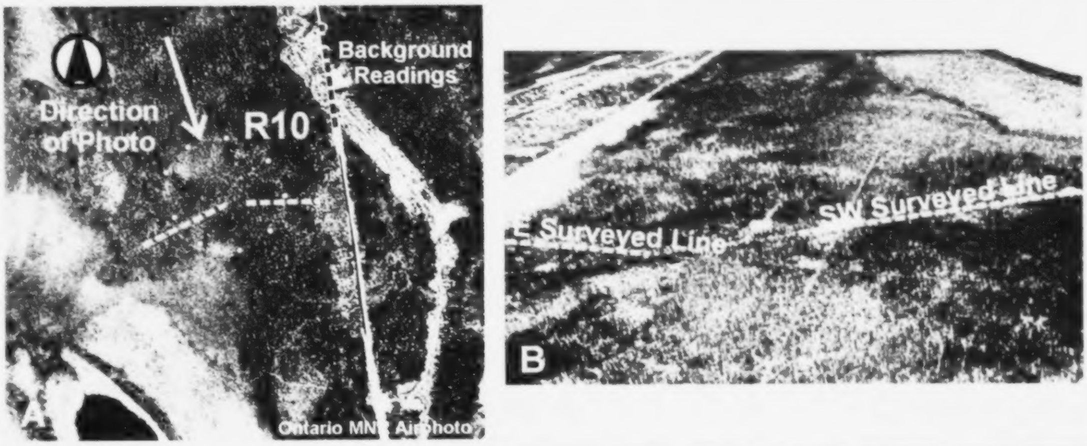


Figure 21.20. Site R10, the "Thorn-North" ring, located 45 km northwest of Timmins, Ontario. The lines visible on the oblique airphoto (B) are drill roads, the 2 of which are labelled were used for laser GasFinder surveys. The location of a background survey is also shown on the satellite image (A).

RESULTS AND INTERPRETATION

Methane Occurrence

The results for the laser GasFinder survey for 9 rings are shown on Figure 21.21. In all cases, the outside of the ring is plotted on the left and the inside on the right and wind direction is plotted at sites where strong winds were encountered. The median values for readings show a clear tendency to be higher inside the ring. Of the 9 sets of readings, R0 SE line, had almost no difference between the inside and outside of the ring and another, the R9 SE line, showed higher readings outside the ring. All others showed higher values inside, although there is generally overlap in the ranges. At both R0 and R9, more than one set of readings were taken and the other sets showed higher responses inside the ring. A possible reason for this was the wind direction at the SE lines of both rings, where the wind was blowing from the inside of the ring out into background areas. On large rings such as these, the small amounts of gas being vented from the ring may be blown out into background areas resulting in a similar response in both areas. This is supported by the readings at R4, which had the same wind conditions and had an apparently diminished response over the ring and at R6 and R9 NW, which had wind blowing *from* background and did not exhibit the same problems. Another possible explanation is that conditions were swampier outside the ring at R9 SE and R0 SE than they were inside the ring. This was arguably also the case at R0 SW, which shows a diminished response and R6, which does not.

Laser GasFinder readings were also taken from the 2 sites that are known or suspected to not be methane-sourced. The response at R2 was considerably higher *outside* the ring than inside it. At R10, the readings on one line were almost the same inside and outside. On another, the readings were higher inside the ring. The reason for this is now known, but the readings near the ring and in a background area nearby were unusually high, perhaps due to very recent logging in and around the ring.

The FID was used at 7 sites and yielded very poor results. The instrument was chosen because it has a greater sensitivity than does a PID, but it has the disadvantage of requiring levels of oxygen in the sampled gas that approach atmospheric. If the oxygen level is too low, the hydrogen flame is extinguished and readings are not possible. Since the sampled medium in the study involves soil gas that often contains large amounts of methane and low oxygen, this normal condition repeatedly caused flame-out. The PID, on the other hand, requires no hydrogen flame and had the added advantage that it was capable of measuring oxygen. The PID results are shown on Figure 21.22.

As discussed, R10 is known to be a non-methane-sourced ring and R2 was strongly suspected of not being associated with methane because of the occurrence of thin drift and outcrop within the ring. These 2 rings have much lower concentrations of methane (note the ten-fold decrease in their respective scales) than the other 3 rings tested with the PID. R1, R3 and R5 have typical anomalous concentrations of methane that are 1 to 2 orders of magnitude higher than those of R2 and R10. Likewise, the oxygen concentrations are much closer to atmospheric at R2 and R10 than at the other 3 rings. A control line was also measured in a swampy area where no rings were present. Oxygen was not measured, but typical methane readings were approximately 25 ppm with 90 ppm being the highest recorded.

Note that the occurrence of methane in association with R1, R3 and R10 does not correlate precisely with the edge of the ring. This had been noted on an earlier occasion at the Bean ring, where methane was still detectable in the headspace of some wells outside the ring, although typically at much lower concentrations.

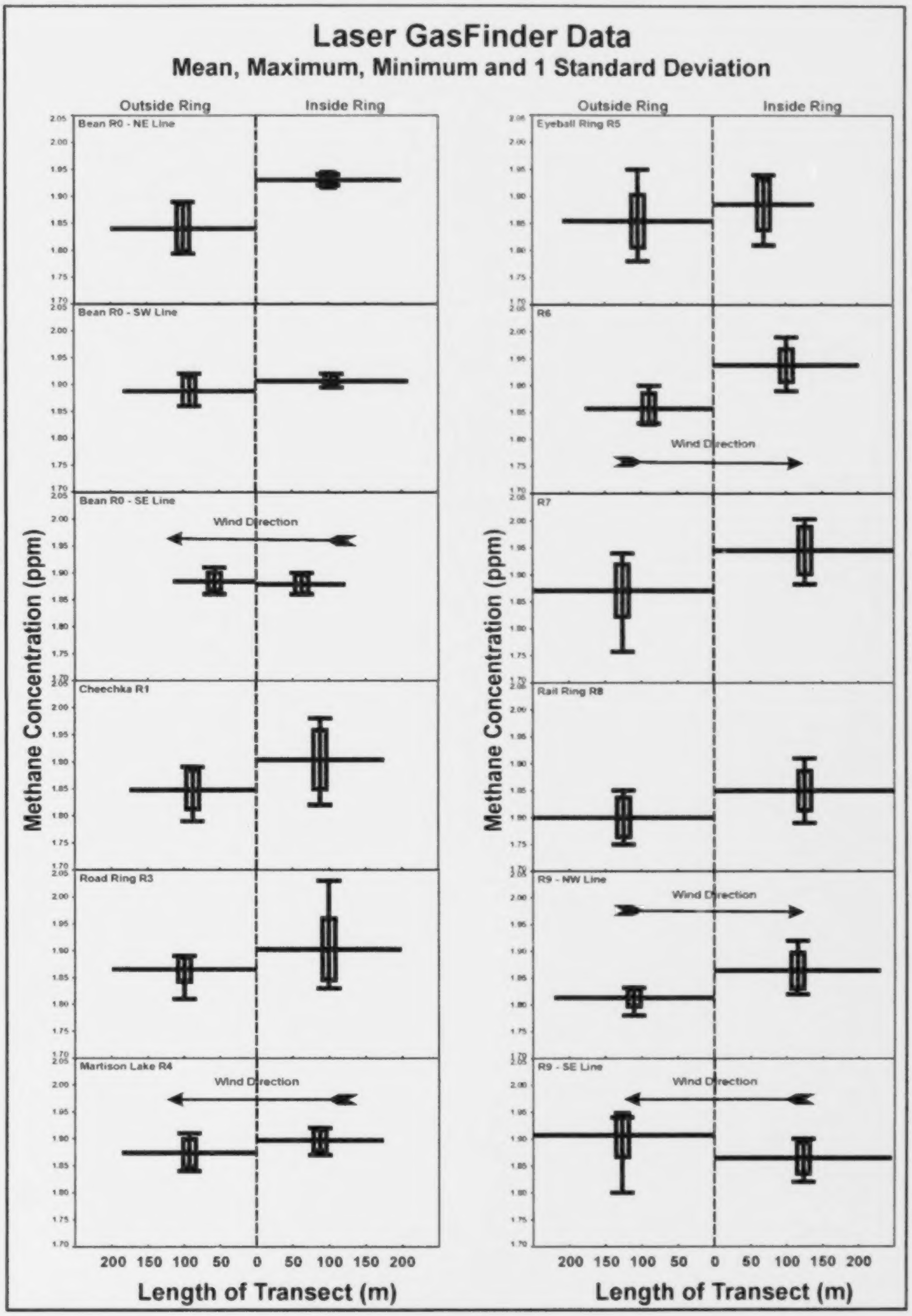


Figure 21.21. Laser GasFinder methane data for transects inside and outside rings in parts per million (the worldwide average methane concentration in air is approximately 1.75 ppm). Horizontal line indicates the mean of readings, vertical boxes indicate one standard deviation from the mean and whiskers indicate total high and low range of readings. Typically, 10 to 15 readings were taken on each transect.

Sources of Methane

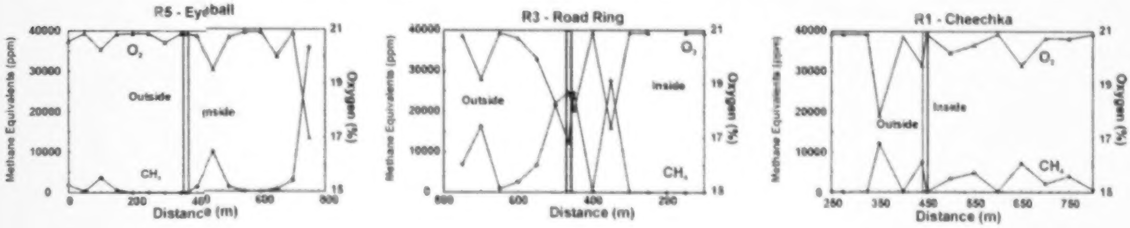
Of the variety of sources of negative charge that could potentially cause rings, such as hydrogen sulphide or molecular hydrogen from kimberlites, methane is undoubtedly the most abundant in the organic terrain of the James Bay Lowlands. The empirical observations in this study have corroborated this with only 2 out of 11 of the rings investigated apparently sourced by reduced materials other than methane and these rings were intentionally chosen as such. It is clear from the distribution of rings and their preponderance in the north half of the study area that they have an association with Phanerozoic rocks and/or fine-grained till and glaciolacustrine sediments. This suggests a variety of possible methane sources:

1. Thermogenic, due to upward migration of natural gas from Phanerozoic rocks of the James Bay Lowlands (or much less likely, the Precambrian rocks beneath these or elsewhere in the study area).
2. Biogenic, from CO_2 reduction of organic materials in the glaciolacustrine and glaciomarine clays and fine-grained tills in the lowlands and to the south.
3. Biogenic, from recent burial of organic matter in lowlands peat.
4. Coal-bed related, due to upward migration from lignite of the Mesozoic Mattagami Formation.

The methane may also be gas hydrate-related, that is, held in gas hydrates until melting of permafrost in the area several thousand years ago. However, this is simply a storage mechanism and the gas would still have to be formed by one of the 4 processes noted above.

In the case of R0, the ring is known to have fairly large quantities of methane *within* the glacial sediments and is not near the Mattagami Formation. This rules out either biogenic peat methane or coal-bed methane in this case. Thermogenic natural gas is also unlikely, since the limestone in this area is less than 50 m thick.

Suspected methane-sourced rings



Known or Suspected non-methane-sourced rings

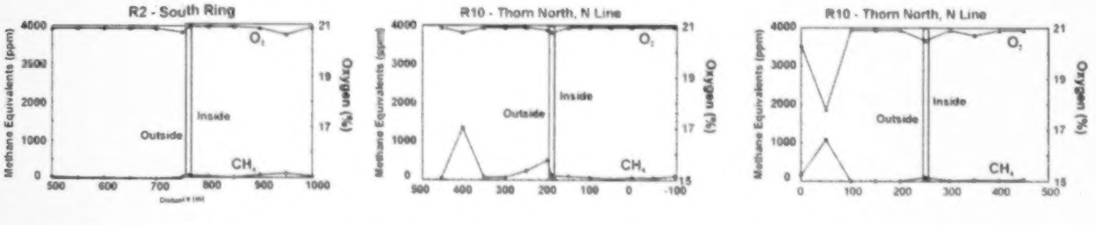


Figure 21.22. Results for photo ionization detector (PID) for methane and oxygen. Note the ten-fold decrease in the methane scale on the bottom 3 plots.

Table 21.1. Carbon isotopic compositions of methane and CO_2 gases, expressed in ‰ relative to PDB (temperatures were calculated using the equation of Horita 2001).

Sample	CH_4	CO_2	1000 ln α (CO_2–CH_4)	Isotopic temperature (°C)*
BE01-shallow	–82.0	–12.1	73.4	13
BE01-deep	not sufficient	–12.1		
BE-11	–79.6	–12.5	70.3	22
BE-16	–87.4	–11.1	80.3	-3.9
BE-21	–75.8	–14.1	64.7	39

Therefore, the most likely source in the case of R0 is due to reduction of CO_2 by organic matter within the clay-rich Cochrane Till. This has been corroborated by the isotope data from methane samples (Table 21.1) collected from 4 shallow wells (9 m depth) near the centre of the site and 1 deep well (40 m deep) in limestone bedrock at the centre.

The $\delta^{13}C$ values for CH_4 from the shallow wells are very low, ranging from –75.8 to –87.4‰. The low values preclude several possibilities (Figure 21.23). For example, methane formed by inorganic processes including thermogenic methane emanating from petroleum reservoirs, has distinctly larger values. The observed values suggest that the methane was formed by bacterial reduction of CO_2. This is supported by the much lower abundance of gas in the bedrock well and the fact that it doesn't contain any methane, which suggest a shallower source of gas.

The $\delta^{13}C$ values for CO_2 (*see* Table 21.1) are slightly lower than those for fresh atmospheric CO_2, which show the range from –7 to –8‰. The lower values are most likely explained by contribution of CO_2 from plants through the respiration of plants and their decay.

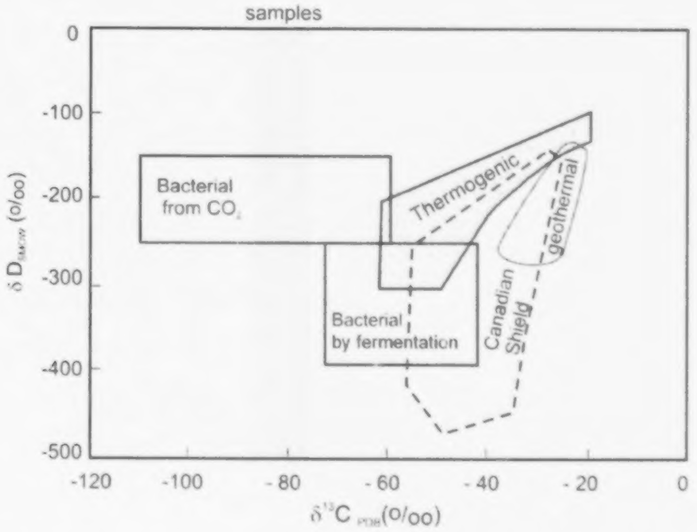


Figure 21.23. $\delta^{13}C$ and δD values of natural methane of different origins. Note that bacterial methane formed by CO_2 reduction have low $\delta^{13}C$ values. Methane of thermogenic origin from petroleum reservoirs show higher $\delta^{13}C$ and δD than that of bacterial origin (*modified after* Hoefs 1997).

Since carbon isotopic compositions of CH_4 and CO_2 are not easily equilibrated, they are commonly used to evaluate the reservoir temperatures (Figure 21.24) after the equation of Horita (2001), below. The difference expressed as 1000 ln α ranges from 64 to 80.

$$10^3 \ln \alpha (CO_2\text{-}CH_4) = 0.16 + 11.754 (10^6/T^2) - 2.3655 (10^9/T^3) + 0.2054 (10^{12}/T^4)$$

Using this equation, the isotopic equilibrium temperatures are calculated to be –4 to 39° C. These low isotopic temperatures are again consistent with a bacterial origin of the CH_4 in the wells at R0.

It should be stressed that the isotope data only exist for a single ring, R0. It is likely that over such a large area, other types of methane will exist in addition to those of biogenic origin. The linear nature of many of the ring clusters suggest localization along bedrock lineaments and this supports a bedrock (i.e., non-biogenic) source of methane in these cases.

SUMMARY AND CONCLUSIONS

A 150 000 km^2 study area in northeastern Ontario was examined using satellite image reconnaissance and approximately 1600 forest rings were identified. Comparison with another proprietary database of rings obtained using airphoto reconnaissance suggests far more rings exist within this area than those that can be identified using Landsat images. Rings are twice as likely to form over Phanerozoic rocks as Precambrian and at least 6 times more likely to overlie Pleistocene glaciomarine sands than in the study area as a whole. A laser spectral absorbance instrument and a photo ionization detector both suggest that the majority of rings in northeastern Ontario are centred on accumulations of methane.

The theory of formation of the rings suggests the methane acts as a source of negative redox charge, maintaining iron in reduced form. The iron ions (Fe^{2+}) migrate outward along redox gradients and oxidize around a perimeter where oxidizing agents are more abundant. This produces acid, which dissolves

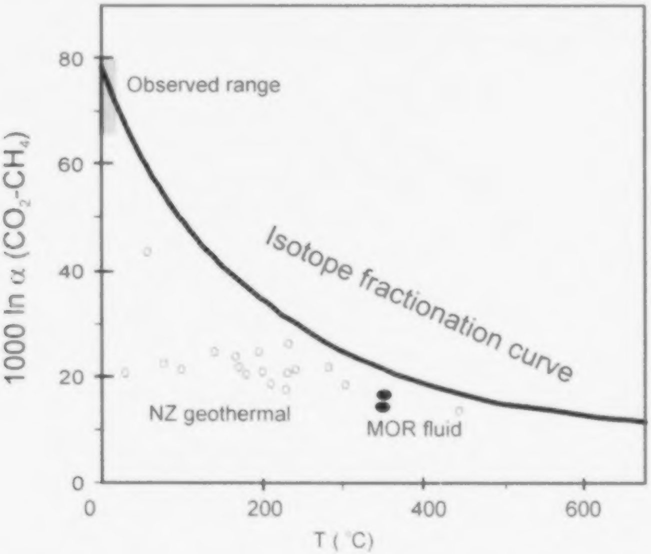


Figure 21.24. Measured difference in $\delta^{13}C$ between CO_2 and CH_4 (1000 ln α) and carbon isotopic fractionation curve by Horita (2001). It also show the values of 1000 ln α and vent temperatures for geothermal fluids in New Zealand (Giggenbach 1997) and the mid-oceanic ridge (MOR: Welhan 1988). Fluids containing CH_4 and CO_2 may cool, but the carbon isotopic compositions of gases retain the reservoir temperatures.

carbonate within the soils causing the ground surface to drop slightly. The resulting combination of lower pH in the soils and greater moisture impacts vegetation making the perimeter visible from the air. The size of the circle is, in part, proportional to the total availability of reducing agents. Larger rings are formed as greater quantities of reduced species migrate outward seeking positive charge until the increasing circumference of the circle balances reducing and oxidizing agents and the outward propagation ceases. The very common clustering of rings of similar size in areas of similar Quaternary geological cover suggests that soil medium also affects ring size. This could only mean different properties in the surficial environment induce different rates of ion migration or the migration of source materials such as methane. Such properties might include either electrical conductivity or permeability.

The circularity of the rings is due to the isotropic nature of the overburden with respect to the migration of ions. If the source of reducing agents is not large enough or is very linear, the process will not form a circle because the perimeter will become sufficiently large to supply the necessary oxidizing agents prior to its expansion into a circular morphology. Therefore, although the process still occurs, it would not be pattern-recognizable as a ring. The rings would also be invisible in areas where no carbonate exists in soils because there would be no resulting depression at the edge of the ring. The non-occurrence of rings in areas of low carbonate has previously been reported (Veillette and Giroux (1999).

The source of methane at one of the rings (R0, the "Bean" ring) has been determined using carbon isotopes to be biogenic reduction of CO_2, probably by organic matter in the clay tills. The Cochrane Till is an over-ridden glaciolacustrine clay unit and in the vicinity of the R0 has numerous sand lenses and seams. It appears that vapour-phase methane occurs within these sand lenses and that it is derived from burial and anoxic decomposition of organic matter within the original lake sediments or till. The nature of that organic matter is at present still a mystery. The much greater preponderance of rings in and around glaciomarine sand units suggests a biogenic source in these areas too. Pleistocene marine organic matter, possibly including plankton may have been entrained within the sediments resulting in later accumulation of methane in the sands. As continuous permafrost yielded to discontinuous in the Holocene, isolated accumulations of permafrost may have preserved methane as gas hydrates in some areas, while allowing its dissipation or oxidation in adjacent areas, thereby producing a sporadic methane distribution and sporadic ring formation.

A deeper, perhaps thermogenic source of gas is suggested in several other areas. Linear occurrences of rings, all of the same size occurs in many areas near the Phanerozoic–Precambrian boundary. A large circle of rings 100 km across and centred on Jog Lake appears not to be associated with marine conditions and many of the rings occur in linear clusters that appear to radiate outward from an area centred on Jog Lake. Further work is proposed for the next field season that includes collecting methane samples from some of these rings to determine the source of gas.

These occurrence of forest rings as an indicator of methane has implications for natural gas exploration. Not only are they indicators of possibly deeper sources of gas, but many are large enough in themselves to possibly be considered as reservoirs of natural gas. The shallow biogenic production of methane from organics in marine sediments has implications for current methane hydrate research being conducted in offshore areas. The release of large amounts of non-peat-related gas also has important implications for climate change.

ACKNOWLEDGMENTS

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22. Project Unit 04-021. Regional Overburden and Water Sampling Survey of the Tweed Area, Southeastern Ontario

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INTRODUCTION

In Ontario, it has been noted that a significant number of kimberlite clusters and other rocks (i.e., lamprophyres) thought to have potential to host diamonds, lie within a broad regional trend that extends from near Attawapiskat in the north, to the Belleville area and beyond, in the southeast (Sage 1998). This regional trend, oriented at 325°, is not defined by a specific geological or geophysical feature, however, along its length is marked by a number of major structural features, for example, the Lake Timiskaming Structural Zone in northeastern Ontario. Kimberlite clusters occur along this regional trend at Attawapiskat, Coral Rapids, Matheson, Kirkland Lake, Temiskaming, Cobalt and Picton in Ontario and Syracuse in New York State (Sage 1998). The kimberlites tend to be located where faults and lineaments or major lithologic boundaries intersect the regional trend.

In southeastern Ontario, the Tweed area and, specifically, Tudor and Grimsthorpe townships have been areas of interest with respect to kimberlite and diamond exploration since the mid-1990s. In addition, a kimberlite dike has been identified in the Essroc quarry at Picton. West- to northwest-trending lineaments found in the region northeast of Tweed are interpreted as a system of faults related to the parallel Ottawa–Bonnechere Graben system. This feature is known as one of the region's principal fault zones and is likely rooted in the lower crust or upper mantle. Such a structure would provide a conduit for mantle-derived kimberlite, lamproite and lamprophyre magmas that are known to transport diamonds to higher crustal levels.

Because of the presence of known kimberlites, deep-seated structural zones and the northwest regional trend, southeastern Ontario provides a favourable environment for diamond exploration. As well, the area has historically seen production of various mineral commodities, including gold, and is favourable for further mineral exploration.

BACKGROUND AND CURRENT STUDY

An overburden sampling survey involves sampling primarily till and modern alluvium stream sediments for a variety of indicator minerals. For diamond exploration, a suite of kimberlite indicator minerals is targeted for recovery. These include pyrope and eclogitic garnets, magnesium ilmenite, chromite, chrome diopside, forsteritic olivine and diamond. The presence of these indicator minerals in overburden samples can be used to determine the prospect for and proximity to any diamond-bearing kimberlites in an area. To assess the precious and base metal mineral potential of a region, other heavy

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.22-1 to 22-9.

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mineral assemblages, including gold grains and metamorphic/magmatic massive sulphide indicator minerals (MMSIM®[2]), are sought for recovery from collected samples.

To evaluate the diamond and other mineral potential of the Tweed area in southeastern Ontario, field work for a regional overburden indicator mineral and water sampling survey was completed by the Ontario Geological Survey during the summer of 2004 (Figure 22.1). The purpose of this study is to establish a baseline of data that will provide regional information on the types and distribution of kimberlite indicator minerals, gold grains and MMSIMs found in overburden sediments. As well, analysis of water samples will provide a baseline of water geochemistry for the survey area. The information will be made public for use by landowners, prospectors, geologists and exploration companies.

The Tweed study area is represented on 8, 1:50 000 scale National Topographic System (NTS) map sheets. Coverage of the study area is provided by the Tichborne (31 C/10), Bannockburn (31 C/12), Bon Echo (31 C/14), and Kaladar sheets (31 C/11), as well as, the northwest corner of the Sydenham sheet (31 C/7), the southeast half of the Coe Hill sheet (31 C/13), the northeast part of the Campbellford sheet (31 C/5) and the north part of the Tweed sheet (31 C/6).

A network of primary and secondary roads and all-terrain vehicle (ATV) trails provided reasonable access to the study area. The presence of numerous lakes and rivers provided boat access to otherwise remote locations.

PHYSIOGRAPHY

The study area is situated in a physiographic region of the Canadian Shield known as the Laurentian Region (Bostock 1976) and, more specifically, within the division known as the Laurentian Highlands. The Laurentian Highlands extend south of the Ottawa River and include the spur of hills formed of Precambrian rocks that cross the St. Lawrence River to form the Thousand Islands. To the south, near Lake Ontario, the highlands gradually disappear beneath the cover of Paleozoic strata (Thurston 1991).

The southeastern edge of the study area is deeply and widely incised by several large rivers that gather volume in the high undulating interior and flow easterly into the St. Lawrence River. As a result, this area has a hilly appearance, with relief commonly between 340 to 680 m above sea level (asl) (Bostock 1976).

Physiographically, the southwest portion of the study area, including Madoc and Huntingdon townships, is divided into 2 parts by the Paleozoic–Precambrian contact that runs along the south side of Moira Lake. The area to the north of Moira Lake forms part of the Precambrian peneplain and slopes southward from an elevation of 305 to 205 m. The region south of Moira Lake is underlain by flat-lying Paleozoic limestone of the Lake Ontario homocline (Hewitt 1968). The Moira and Black rivers and their tributaries, which flow into Lake Ontario, drain the area.

The northwest part of the study area lies within the Cashel peneplain division of the Lake Ontario homocline. The Cashel peneplain is a resurrected, glaciated Precambrian erosion surface with a local relief of about 30 m and a gentle southward slope (Lumbers 1969). There is a gradual increase in elevation from south to north that is locally interrupted by resistant rock masses, mainly plutonic rocks, with higher elevations than those of the surrounding country (Lumbers 1969). Most of the lake basins in this area occur at contacts between marble and rocks more resistant to erosion than marble. Other lakes lie in the cores of synclinal folds developed in underlying metasediments. This part of the study area is drained by 3 major river systems: the Moira, Trent and Madawaska (Lumbers 1969). The Madawaska River system forms part of the Ottawa River drainage basin while the other 2 belong to the Lake Ontario drainage basin (Lumbers 1969).

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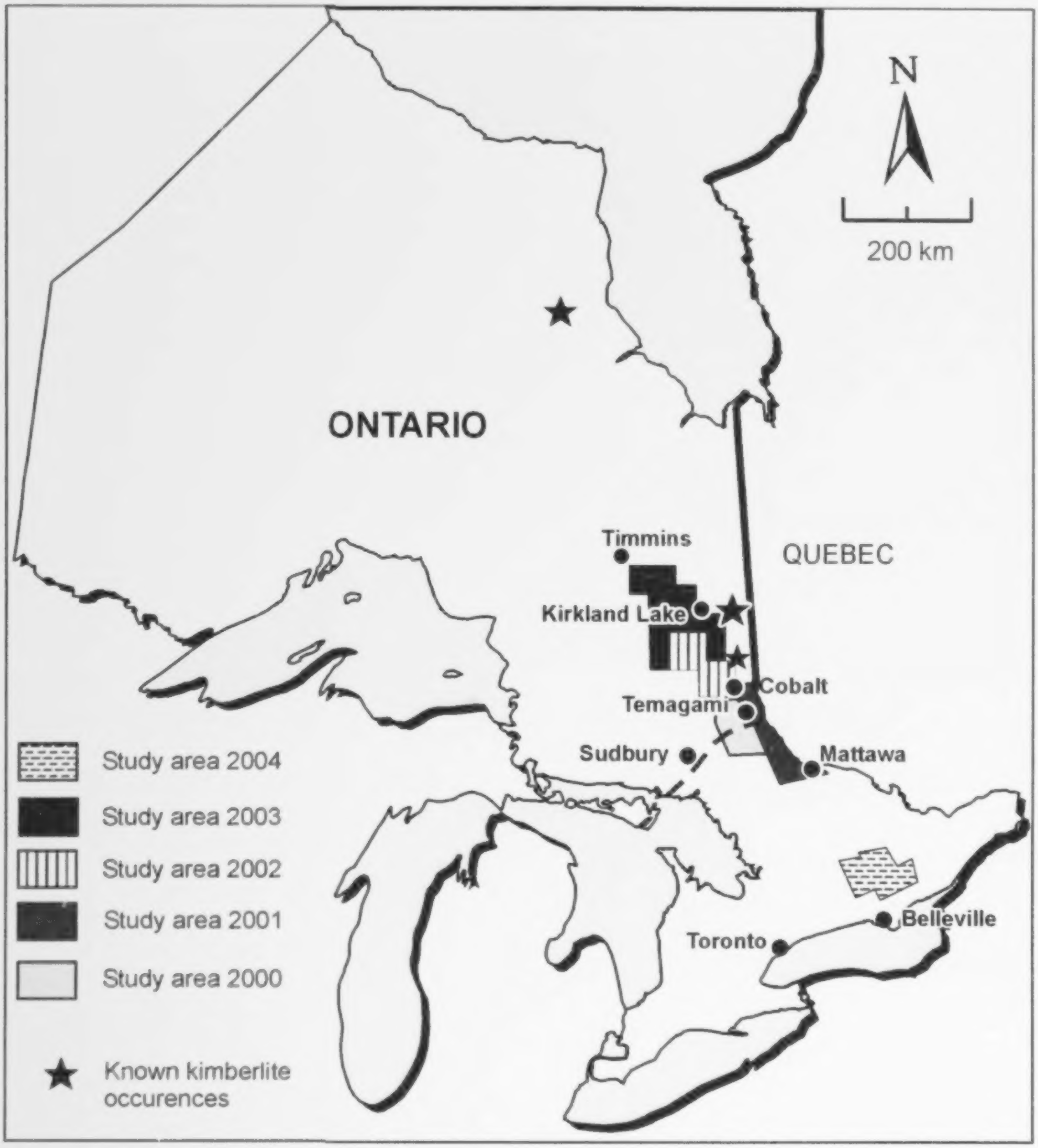
[2] MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario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200 km
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QUEBEC
Timmins
Kirkland Lake
Cobalt
Temagami
Sudbury
Mattawa
Toronto
Belleville
Study area 2004
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Study area 2002
Study area 2001
Study area 2000
Known kimberlite occurences

Figure 22.1. Location of the 2004 study area in relation to other indicator mineral surveys recently completed by the OGS in northeastern Ontario. Locations of known kimberlites *from* Sage (1996).

Relief around the central part of the study area (Kaladar) is quite varied, ranging from 35 to 325 m asl (Wolff 1982a). Swamp-filled valleys situated between northeast-trending bedrock ridges provide the major drainage pathways for this region. All waterways in this area drain to the south or southwest. The Salmon (flowing south from Kennebec Lake) and Skootamatta rivers, both located in this area, feed the Moira River drainage system (Wolff 1982a). Distribution of rock outcrop is variable in this region and swamp-covered valleys tend to be underlain by carbonate metasedimentary rocks (Wolff 1982a).

The eastern part of the study area is characterized by elevations ranging from 185 to 260 m asl. However, the area, in general, is of low relief (Wolff 1982b). The area represents a water divide between Lake Ontario and the Ottawa River (Wolff 1982b). Distribution of rock outcrop is quite variable through this region.

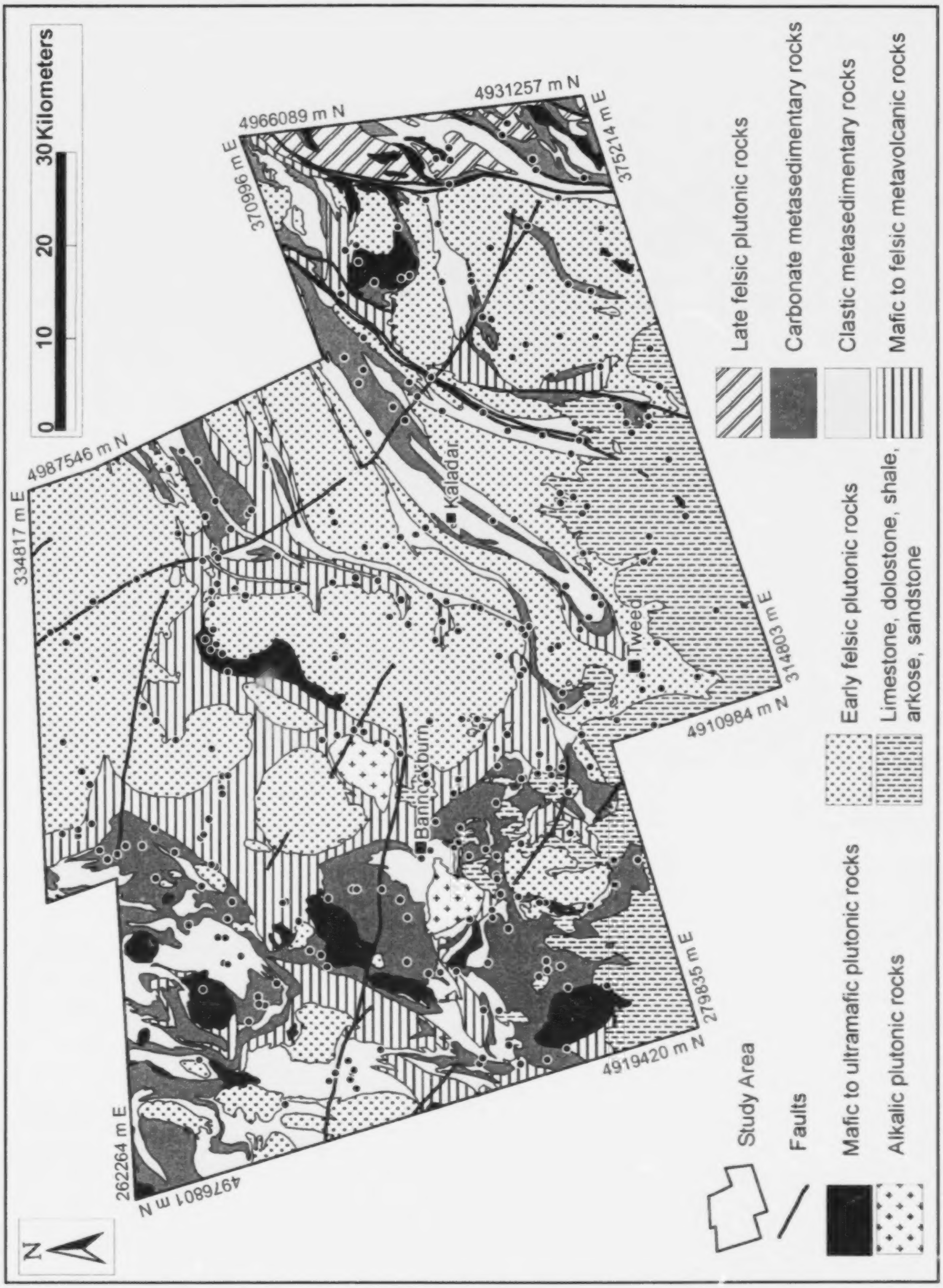
BEDROCK GEOLOGY

The oldest rocks in the study area are Neo- to Mesoproterozoic (0.57 to 1.6 Ga) age and belong to the Grenville Province. These rocks include those that compose the Central Metasedimentary Belt and the Grenville Supergroup and Flinton Group. The Central Metasedimentary Belt is a major Mesoproterozoic accumulation of metavolcanic supracrustal rocks and metasedimentary rocks of the Grenville Supergroup invaded by compositionally diverse, syntectonic, late tectonic and post-tectonic plutonic rocks (Easton 1992). Locally, late tectonic pegmatite sheets and dikes cut the supracrustal rocks (Wolff 1982a) (Figure 22.2).

Rocks comprising the Central Metasedimentary Belt include mafic to ultramafic plutonic rocks (diorite, gabbro, peridotite, pyroxenite and anorthosite); alkalic plutonic rocks such as nepheline syenite, alkalic syenite and associated mafic, ultramafic and carbonatitic rocks; and felsic plutonic rocks such as granodiorite, tonalite, monzogranite, syenogranite and derived gneisses and migmatites (Ontario Geological Survey 1991). The rocks that comprise the Grenville Supergroup and Flinton Group include carbonate metasedimentary rocks such as marble, calc-silicate rocks, skarn and tectonic breccias; clastic metasedimentary rocks such as conglomerate, wacke, quartz, arenite, arkose, limestone, siltstone, chert and minor iron formation; and mafic to felsic metavolcanic rocks that include flows, tuffs, breccias, minor iron formation and minor metasedimentary rocks (Ontario Geological Survey 1991).

The northwestern part of the survey area is underlain by a Proterozoic complex of metavolcanic and metasedimentary rocks that increase in metamorphic grade from south to north. As well, a large variety of intrusive rocks form numerous stocks exposed over areas ranging from a few hundred square metres to approximately 75 km^2.

The southern and southwestern parts of the survey area straddle the Paleozoic–Precambrian contact. Overlying Precambrian bedrock south of the contact are Middle Ordovician rocks belonging to, in ascending order, the Shadow Lake, Gull River and Bobcaygeon formations (Ontario Geological Survey 1991). The lowermost Shadow Lake Formation consists of quartz-rich, red siltstone and shale, arkosic sandstone and polymictic conglomerate (Lumbers 1969). The overlying Gull River Formation consists of lithographic and sublithographic limestone and dolostone (Carson 1981). The Bobcaygeon Formation consists of crystalline and bioclastic limestone (Carson 1981).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262264 m E
4976801 m N
Kaladar
Tweed
Bannockburn
Study Area
Faults
Mafic to ultramafic plutonic rocks
Alkalic plutonic rocks
Early felsic plutonic rocks
Limestone, dolostone, shale, arkose, sandstone
Late felsic plutonic rocks
Carbonate metasedimentary rocks
Clastic metasedimentary rocks
Mafic to felsic metavolcanic rocks

Figure 22.2 Regional bedrock geology of study area (*after* Ontario Geological Survey 1991).

ECONOMIC GEOLOGY

The study area has seen the historic production of a variety of industrial, precious and base metals. Many of the deposits and operations have been of limited size, however, some larger extractive operations have existed. The more significant operations are highlighted below.

Numerous contact metasomatic magnetite deposits occur in the southern part of the Grenville Province (Lang et al. 1976). These deposits are relatively small and many were worked out during the 19th century. At Marmora, a very large deposit of magnetite was discovered beneath 40 m of Paleozoic limestone by an aeromagnetic survey conducted during 1953. Mining of the deposit began in 1955 and operations ceased in 1978. The mass of ore was over 800 m long and 125 m wide and contained an average of 40% iron. At the height of production about a half a million tons of pellets containing 65% iron was produced annually (Lang et al. 1976).

Fluorite, barite and celestite have been found in veins that occur within Precambrian and Paleozoic rocks of the study area. In the Madoc area, 2 vein systems known as the Moira Lake and Lee–Miller groups were exploited for the commercial production of fluorite. Veins of the Moira Lake group centre on a northwest-trending fault. Most of the veins lie in the fault fissure, however, some occur in parallel subsidiary fractures. The Lee–Miller group lies approximately 2 km west of the Moira Lake group and forms a string of north-trending deposits. Here, numerous vugs are filled with fluorite that is either partly massive or partly crystalline. Production from these veins occurred mainly during the Second World War. Production ceased in 1961 after an estimated 120 000 tons had been mined (Lang et al. 1976).

Talc has been produced from Precambrian rocks near Madoc for over 100 years. Canada Talc, a division of Dynatec, presently operates a talc mining operation just south of Madoc at the Henderson and Conley mines (Lang et al. 1976). A small amount of asbestos was produced from an unusual deposit in Bannockburn Township. There, veinlets of asbestos occur in a shattered zone of rhyolite at its contact with a highly serpentinized body of peridotite (Lang et al. 1976).

A number of quarries in the Tweed, Kaladar and Bannockburn areas of southeastern Ontario have extracted limestone and dolostone from the lower member of the Bobcaygeon Formation and the middle and upper members of the Gull River Formation. Products included railway ballast, concrete aggregate and road metal. A number of abandoned quarries including the Robindale, Crookston Main and Tweed are found in this area. Other smaller abandoned quarries are also found around Eldorado, Crookston and Madoc. A few large, active quarry operations exist in the study area. AECON, located in Marmora, quarries limestone for aggregate while traprock has been produced by I.K.O. Industries Ltd., from a quarry at Madoc since 1991 (Sangster et al. 2002). The Upper Canada Stone Co. operates a quarry just north of Madoc for the production of marble chips (terrazzo).

The Kaladar area contains a variety of metallic and non-metallic mineral deposits, however, the only significant, historic producer on record is the Addington gold mine near the village of Flinton. Minor surface workings for actinolite, quartz, feldspar and mica were active in the area from the late 1800s until 1940.

Madoc and northern Huntingdon townships were mined for numerous economic minerals including barite, fluorospar, gold, iron and copper, lead, marble and limestone, pyrite, slate, talc and stone for roofing granules (Hewitt 1968).

Within Limerick and Tudor townships, the most common type of mineralization consists of pyrite- and pyrrhotite-bearing, rusty weathering schist zones. In these zones, the pyrite and pyrrhotite are present as disseminated grains and as locally developed massive streaks and lens-like bodies. Gold, arsenic, copper, nickel, iron, titanium, lead, zinc, silver, bismuth, barite and talc mineralization have also been found within these townships (Lumbers 1969). Various marble deposits have been exploited for the production of roofing granules.

Toward the eastern part of the study area, in Frontenac County, metallic mineralization consists mainly of zinc, lead, copper, nickel and iron. Zinc, copper, nickel, cobalt, iron and gold occurrences tend to be limited to the Mountain Grove mafic intrusion (Wolff 1982b).

Sand and gravel production has occurred at many locations in the survey area (Liberty 1963), however, many of these sites are now depleted and have been abandoned.

QUATERNARY GEOLOGY

During the Wisconsinan Episode, the study area was periodically covered by glacial ice of the Laurentide Ice Sheet. Glacial deposits of the area are considered to be the result of the last glacial stage, the Late Wisconsinan (Barnett 1992). Two major lobes of the Late Wisconsinan ice-sheet affected the central and eastern parts of southern Ontario: the Lake Ontario lobe, which advanced westward into the Lake Ontario basin from the St. Lawrence and Ottawa valleys; and the Northern lobe, which advanced southward across the central part of southern Ontario to the Lake Ontario basin. The orientation of glacial striae and drumlins indicate that the study area was affected only by the Northern lobe (Lumbers 1969).

Glacial deposits of the southwestern portion of the study area consist mainly of bouldery ground moraine (till) and kame moraines. Within Madoc Township, the kame moraines have been exploited for sand and gravel (Hewitt 1968). Glacial deposits in the northwestern part of the survey area include till in the form of ground moraine and drumlins (Lumbers 1969). Locally, numerous small deposits of sand and gravel overlie and, in places, are interstratified with the ground moraine.

In the central part of the survey area, glacial deposits include ice-contact sediments, glaciofluvial outwash and till. Near Kaladar, 2 prominent sand-rich glaciofluvial outwash deposits are present. Other glacial features of this area include drumlins and eskers located near Tweed and Foxboro (Liberty 1963). Along the Skootamatta River and Little Skootamatta Creek, bedrock exposures display chattermarks and potholes (Wolff 1982a).

The eastern portion of the survey area is characterized by a narrow band of glacial deposits that occupy the major shear zone which passes through the village of Mountain Grove (Wolff 1982b). Deposits are varied and comprise ice-contact stratified drift; eskers, kames, kame moraines and minor till. Local aggregate operators actively work sand and gravel-rich deposits in this area.

Recent deposits are found throughout the entire survey area and consist mainly of organic swamp, lake and stream deposits (Wolff 1982a, 1982b; Lumbers 1969).

REGIONAL SAMPLING SURVEY

The current regional overburden and water sampling survey, covering a total area of approximately 4700 km^2, was conducted in June, July and August 2004. A total of 300 overburden samples (161 modern alluvium, 74 till, 15 glaciofluvial sand and gravel and 50 beach deposit) were collected. A total of 203 water samples were collected, one at each of the stream and beach deposit sites. Access to sample locations was achieved by truck, ATV and boat. The resulting distribution of collected samples provides excellent regional coverage. Regional overburden sampling surveys provide data on the types, distribution and relative concentration of heavy minerals in a given region. The number of samples collected was predetermined by budget and time considerations, however, samples were collected over as broad an area as possible. The position of each sample was accurately recorded with a global positioning system (GPS) instrument set to North American Datum 1983 and 1927 (NAD83 and NAD27, respectively) and using NTS 1:50 000 scale map sheets situated in Universal Transverse Mercator (UTM) zone 18.

Modern alluvium was chosen as the primary sampling media for this study as it provides a means of obtaining a fast, relatively inexpensive heavy mineral signature for individual drainage basins (Morris et al. 2000). Points of heavy mineral deposition within streams were targeted for sample collection. Sampling points included: the deepest part of the channel; longitudinal and point bars; and boulder, log and vegetation traps (Morris et al. 2000). Material was sieved in the field using a 5 mm mesh screen and the finer fraction (<5 mm) was retained. Sample weight ranged from 10 to 20 kg. At some sites, larger samples were collected to compensate for either a high percentage of fine sand or silt material in the sediment or the dilution of heavy mineral grains caused by a high percentage of organic material. The <5 mm fraction of the sample was sent for heavy mineral processing to separate possible kimberlite and other indicator minerals. Where possible, approximately 50 pebbles were collected from the coarser (>5 mm) fraction at each sample site for pebble lithology classification. Pebble lithologies classified to date indicate that, typically, stream deposits are locally derived. In addition, at each site, a small portion of the stream sediment was panned and the resultant "fine-fraction" concentrate retained. At those sites where other overburden materials were sampled (e.g., till), similar sample collection protocols were followed.

At each sample location, a site description consisting of observations, as applicable, on: a) genesis of material, stream flow and depth; b) surface expression; c) slope inclination and aspect; d) drainage; e) vegetation type and state; f) glacial features; g) anthropogenic factors; h) material description consisting of: i) texture; ii) structure; iii) bar form, iv) clast size, abundance, shape and type; i) diagrams and additional comments; and j) pH of water sample, was completed. Photographs were taken at several sites.

Water sampling involved the collection of 60 mL of water into a sterile plastic bottle. At each site, a pH reading of the stream or lake water was also recorded. At the end of each day, water samples were filtered and acidified using nitric acid. A sub-sample of acidified water was transferred to a 25 mL sterile bottle and retained for laboratory analysis. At the end of the field season, conductivity measurements were completed for each water sample. All water samples have been submitted to the Ontario Geological Survey Geoscience Laboratories, Sudbury, Ontario, for the determination of approximately 50 elements by direct aspiration inductively coupled plasma mass spectrometry (ICP–MS).

Results from the study are expected to be released in 2005.

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23. Project Unit 04-023. Upper Manitou Lake Area High-Density Regional Lake Sediment and Water Survey, Northwestern Ontario

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INTRODUCTION

Field work for a high-density lake sediment and water geochemical survey in the Upper Manitou Lake area of northwestern Ontario was carried out from June 9 to July 1, 2004. The survey area is located approximately 240 km northwest of Thunder Bay and is represented on National Topographic System (NTS) 1:50 000 scale map sheets 52 F/7 and 52 F/8. This survey covers approximately 2000 km^2 (Figure 23.1). Lake sediment and/or water samples were collected at 1087 sites for an average density of 1 sample per 1.9 km^2.

The Upper Manitou Lake area was selected for this type of survey for reasons including client interest, geology with favourable mineral potential and a lack of detailed geochemical exploration data for the region. The present survey lies immediately south of the Sturgeon Lake–Wabigoon Lake lake sediment survey carried out in 2001 (Russell 2004). The National Geochemical Reconnaissance (NGR) lake sediment program carried out by the Geological Survey of Canada in 1988 covered the current survey area (Hornbrook and Friske 1989), but at a much broader scale (an average of 1 sample per 13 km^2). The results of the current program will provide new regional geochemical data at a relatively high resolution.

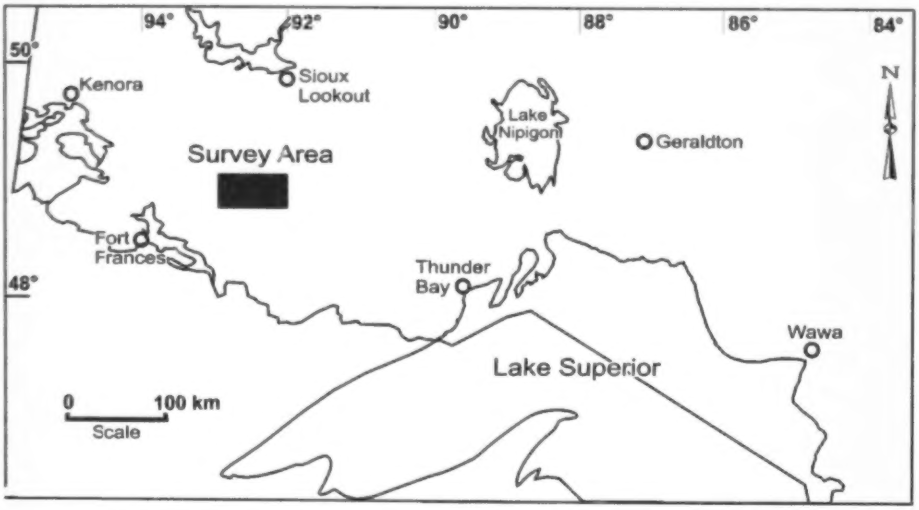

Figure 23.1. Location map of the Upper Manitou Lake survey area.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.23-1 to 23-6.

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REGIONAL GEOLOGIC SETTING

Bedrock Geology

The Upper Manitou Lake survey area lies within the western Wabigoon Subprovince, a granite-greenstone terrane of the Superior Province. The survey area encompasses most of the Eagle–Wabigoon–Manitou lakes greenstone belt. This greenstone belt is an arcuate structure 20 km wide and 80 km long, extending from Lower Manitou Lake on the west to Bending Lake on the east, and tapering at either end (Blackburn 1982). To the southwest, the belt that can be traced uninterrupted via Kakagi Lake to Lake of the Woods, while to the north the belt joins with metavolcanic rocks that extend northward towards Dryden (Blackburn 1979).

In general, the belt consists of a lower mafic metavolcanic unit (Wapageisi group), middle mixed intermediate to felsic metavolcanic and metasedimentary units (Manitou Lake and Stormy Lake groups) and an upper mafic to intermediate metavolcanic unit (Upper Wabigoon Volcanics and Boyer Lake groups). The massive to pillowed magnesium and iron-tholeiitic and komatiitic rocks of the Wapageisi group are conformably overlain by calc-alkalic pyroclastic rocks, minor mafic flows and associated sediments of the intermediate Manitou Lake metavolcanic group (Blackburn et al. 1991).

The western portion of the survey area is cut by the northeast-striking Manitou Straits fault. A fault of considerable magnitude, it extends through the Manitou straits and northward to Kabagukski Lake. The fault is marked by a zone of highly fissile phyllitic and schistose rocks and is no more than 30 m wide (Blackburn 1982).

Supracrustal rocks are intruded by a number of granitic bodies including the Atikwa batholith to the northwest, the Irene–Eltrut Lakes batholithic complex in the south-central portion of the survey area and the Revel batholith to the west. As well, 2 smaller plutons, the Taylor Lake pluton (~2695 Ma) and the Scattergood Lake pluton (~2700 Ma) occur within the Eagle–Wabigoon–Manitou lakes greenstone belt. Many of these small, late plutons exhibit a close spatial relationship with gold ± copper ± molybdenum mineralization (Blackburn 1981).

Regional bedrock mapping shows that most past producing mines and mineral showings are concentrated in and adjacent to the northeast-trending sequences of volcanic and sedimentary rock. Mineral deposits occur in a variety of lithologies including volcanic, sedimentary and deformed granitoids. Precious metals (Au, Ag, Pt) and associated sulphides are the most common mineralization (Minning et al. 1994).

Physiography and Surficial Geology

Engineering geology terrain maps have been produced for the area at a scale of 1:100 000 (Roed 1980). The Geological Survey of Canada also produced detailed surficial mapping for the survey area at the same scale (Minning et al. 1994). Quaternary sediments in the survey area are described as generally thin and patchy, with the exception of the Eagle–Finlayson moraine and in areas where glaciolacustrine deposits of glacial Lake Agassiz fringe the moraine. The Eagle–Finlayson moraine is a sharp-crested, single ridge moraine composed of sand and gravel that rises over 30 m above the surrounding land and can be traced for over 240 km (Zoltai 1961).

Topography in the Upper Manitou lakes area is typical of that of much of the Canadian Shield, consisting of rolling and knobby rock-buttressed landforms with numerous lakes and bogs (Roed 1980). Topography and drainage patterns in the area are a result of modification by the scouring action of glacial ice upon various bedrock lithologies and structures (Blackburn 1979). Relief in the survey area is variable and ranges from 371 to 457 m asl (Roed 1980).

SAMPLING METHODS

Sampling of organic lake sediments was performed using a float-equipped Bell 206B helicopter. Where access was available and the number of samples warranted, some lakes were sampled from a 17-foot aluminium boat with a 25-horsepower motor. An overall average of 14 lakes were sampled for each hour of helicopter time. The samples were collected using an OGS-designed gravity corer which was lowered from the helicopter float and then pulled to surface. Samples were taken from depths greater than 20 cm below the sediment–water interface (SWI) in order to minimize or avoid anthropogenic influences and SWI effects. These deeper sediments more accurately reflect geochemical effects which may be attributed to the local geology. The samples were extruded from the collection tube into breathable fabric bags and then placed in a sealable plastic bag until the end of the sampling run. If a site contained no organic component (e.g., sand and/or clay), only a water sample was taken.

Lake water samples were taken upon landing at a sample site, prior to the collection of sediment samples. On lakes less than 3 m deep, samples were collected at 0.5 m below the water surface; on lakes deeper than 3 m samples were collected at a depth of 2 m. A semi-automated water sampling apparatus, developed by the OGS and consisting of a pump, a YSI multiparameter water-quality analyzer (for measurement of parameters such as pH, temperature and conductivity), a sample bottle tray and a variety of hoses and valves, was used for sample collection. Lake water is pumped through the system in order to purge it prior to the collection of a sample and the recording of water-quality data. The water samples were kept cool immediately following collection and were processed (filtered and acidified) within 24 hours of collection.

Sample site locations were recorded using a global positioning system (GPS) receiver mounted in the cockpit of the helicopter. Sediment sample information and descriptions were recorded on standardized forms and later entered into a Microsoft® Access database. Water quality data was recorded using a hand-held data logger and transferred to a computer at the end of each sampling run. GPS co-ordinates of each sample site location were also downloaded to a computer at the end of each field day.

SAMPLE PREPARATION AND ANALYTICAL METHODS

Lake sediment samples were partially air dried in porous collection bags while in the field. Upon return from the field, samples were dried, partially pulverized in a ceramic ring mill and sieved to obtain the –80 mesh (<177 μm) size fraction. Samples will be submitted for a variety of laboratory analyses. Samples will be subjected to nitric–aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP–MS) and inductively coupled plasma optical emission spectrometry (ICP–OES) to determine approximately 50 trace and major elements. Nitric–aqua regia digestion attacks all sample matrix constituents except for silicate minerals and is therefore considered a non-selective, relatively strong partial extractant. Approximately 15 g of sample pulp will be pressed into briquettes prior to analysis by instrumental neutron activation analysis (INAA) for gold and 34 other elements. Loss on ignition (LOI) is determined at 500°C using an automated gravimetric technique. Quality control for all analyses is monitored through the use of certified reference materials placed regularly through the sample sequence and randomly taken sample pulp duplicates.

Water samples were passed through 0.45 μm syringe filters and acidified to approximately 1% ultrapure nitric acid in the field. Analysis of water will be completed by direct aspiration ICP–MS to determine approximately 50 elements. Quality of the analyses will be monitored through the use of blanks, National Research Council certified reference standard SLRS-4, and random sample duplicates.

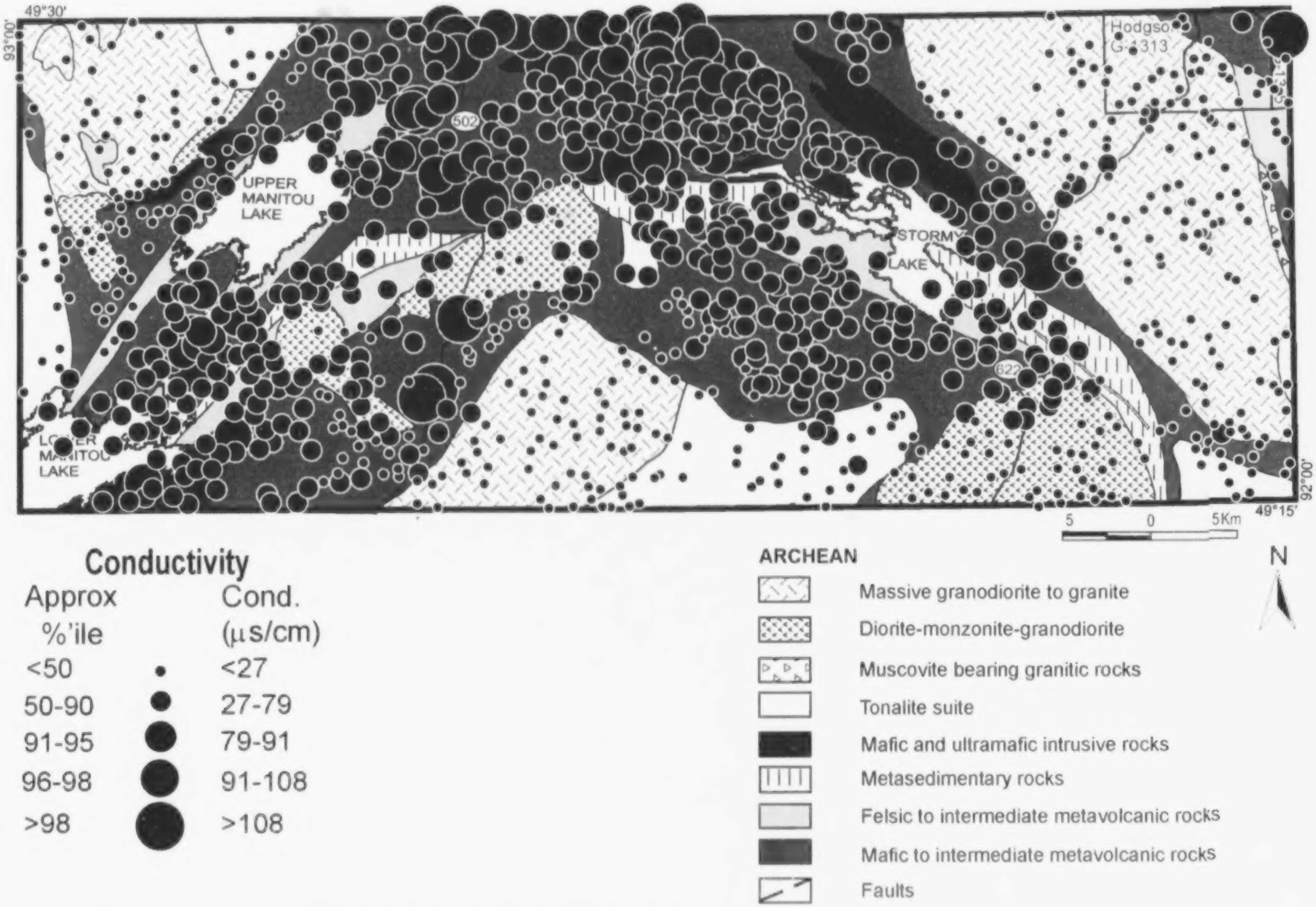
49°30'
93°00'
UPPER MANITOU LAKE
LOWER MANITOU LAKE
STORMY LAKE
502
622
Hodgson G-4313
G-1325
92°00'
49°15'
5
0
5Km
N
Conductivity
Approx %'ile
Cond. (µs/cm)
<50 • <27
50-90 ● 27-79
91-95 ● 79-91
96-98 ● 91-108
>98 ● >108
ARCHEAN
Massive granodiorite to granite
Diorite-monzonite-granodiorite
Muscovite bearing granitic rocks
Tonalite suite
Mafic and ultramafic intrusive rocks
Metasedimentary rocks
Felsic to intermediate metavolcanic rocks
Mafic to intermediate metavolcanic rocks
Faults

Figure 23.2. Generalized bedrock geology and electrical conductivity in lake waters. Geology *after* Ontario Geological Survey (1991).

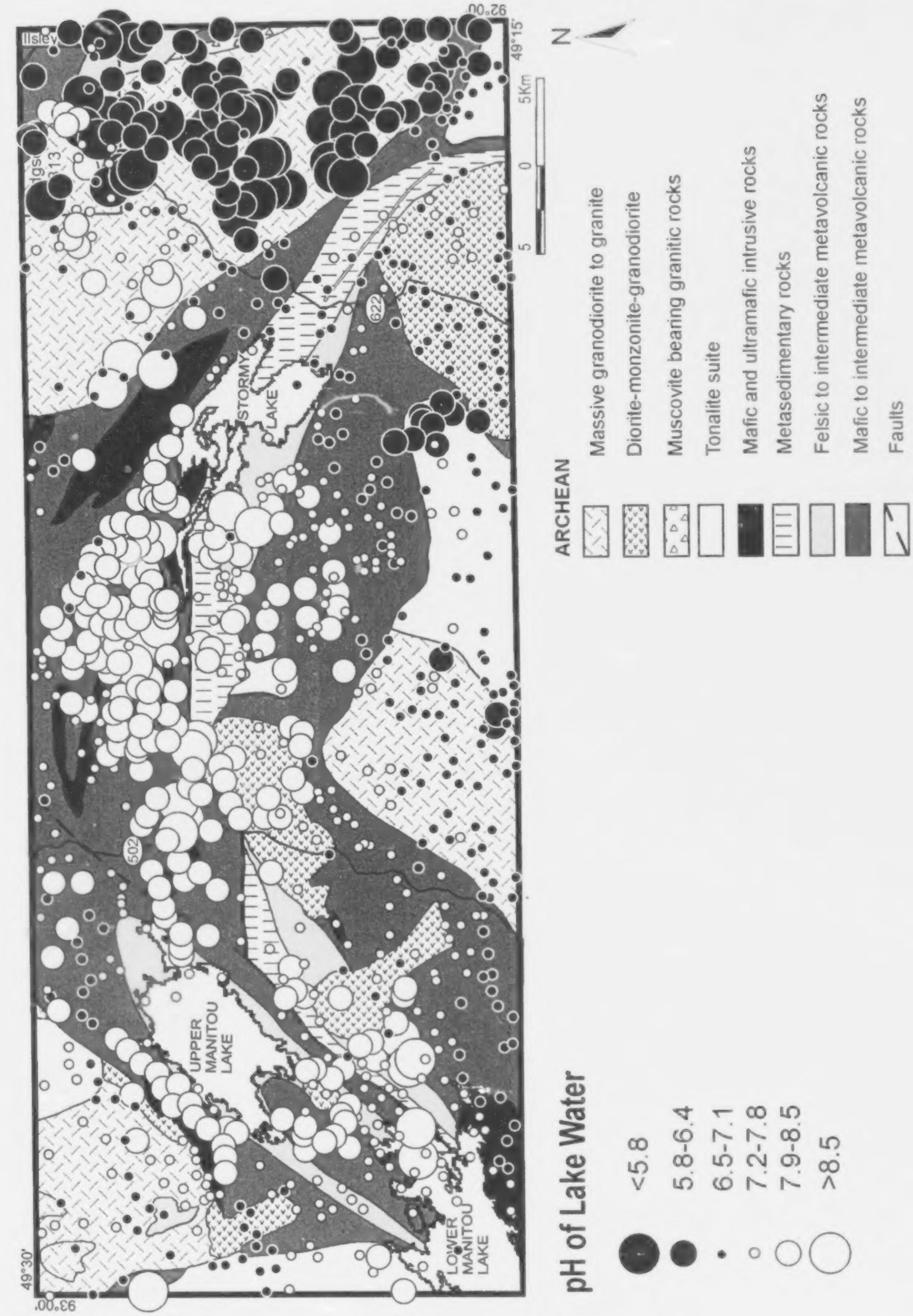
Ilsley
313
49°30'
93°00'
92°00'
49°15'
N
5
0
5Km
STORMY LAKE
622
502
UPPER MANITOU LAKE
LOWER MANITOU LAKE
pH of Lake Water
<5.8
5.8-6.4
6.5-7.1
7.2-7.8
7.9-8.5
>8.5
ARCHEAN
Massive granodiorite to granite
Diorite-monzonite-granodiorite
Muscovite bearing granitic rocks
Tonalite suite
Mafic and ultramafic intrusive rocks
Metasedimentary rocks
Felsic to intermediate metavolcanic rocks
Mafic to intermediate metavolcanic rocks
Faults

Figure 23.3. Generalized bedrock geology and pH in lake waters. Geology *after* Ontario Geological Survey (1991).

PRELIMINARY RESULTS

Electrical conductivity (EC) values in lake waters obtained in the survey area range from less than 10 to 176 µS/cm, with an average of 38 µS/cm and a median of 27 µS/cm. Figure 23.2 shows the distribution of conductivity in lake water across the study area. The relatively low lake water conductivities (and therefore low element loadings into the lakes) throughout the study area is consistent with the lack of thick, continuous glacial drift cover. The observed patterns may, in part, reflect bedrock geology. For example, most of the conductivity values greater than the 90th percentile of the data set (>79 µS/cm) occur in areas underlain by, or in close proximity to, bedrock mapped as either metavolcanic or metasedimentary rocks. The lower values of the data set occur in primarily granitic bedrock areas. Some of the highest values are found in close proximity to roads or highways, which may suggest some influence from contaminants (road salt, etc.).

Values for pH in lake waters range from 4.20 to 8.79, with an average of 7.28 (Figure 23.3). As with electrical conductivity, bedrock geology appears to be the major factor affecting pH values. Greenstone belt rocks show a more alkaline response (average pH of 7.57), whereas granitic rocks are slightly acidic (average pH of 6.85). Acidic conditions in the eastern portion of the survey area are typical of the Canadian Shield and reflect the low buffering capacity of granitic rocks and the lack of any significant surficial materials to provide buffering capacity. Neutral to alkaline pH values in the north central portion of the survey area may reflect the underlying bedrock geology (i.e., greenstone belt rocks, in particular mafic rocks with a naturally higher level of Ca). This response may also be evidence for the presence of carbonate bearing drift material. Minning et al. (1994) have documented the presence of some carbonate clasts and some carbonate rich drift in the region.

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24. Project Unit 02-018. Three-Dimensional Mapping of Quaternary Deposits in Waterloo Region, Southwestern Ontario

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INTRODUCTION

In 2002, the Ontario Geological Survey (OGS) embarked on a project of three-dimensional mapping of Quaternary deposits within the Regional Municipality of Waterloo (RMOW). This project is being undertaken as part of a broader geoscience initiative designed to provide basic geoscience information for the protection and preservation of the provincial groundwater resource. The main objective of this project is to characterize, in 3 dimensions, the geometry and intrinsic properties of subsurface Quaternary deposits. This work will aid studies involving groundwater extraction, protection and remediation, to assist with the development of policies surrounding land use and nutrient management and to better understand the interaction between ground and surface waters.

Three main areas of work have been ongoing over the past 2 years. These can be summarized as 1) data compilation and standardization; 2) acquisition of new geologic and geophysical data; and 3) data interpretation, synthesis and presentation. The project is currently in the interpretation and synthesis phase.

ASSEMBLY OF THE SUBSURFACE DATABASE

The project working database contains records from a variety of sources of varying data quality. It contains in excess of 35 000 records and nearly 100 000 sediment layers. Approximately half of the records are classified as "definitive" meaning they were logged by a trained geoscientist. These records are critical for the successful development of a subsurface geologic model. The remaining records belong to the Ontario Ministry of the Environment (MOE) water well database and have compromising issues related to positional accuracy and coding reliability. These records are used to build the model in areas lacking high-quality information as well as to bolster the model in well-understood areas. Details regarding the data sources are contained in Bajc et al. (2003).

The project database is continually updated as new records become available. In 2004, the main additions to the database were the detailed logs of 13 continuously cored boreholes as well as a suite of approximately 450 high resolution lithologic logs. The latter were derived from a detailed interpretation of archived borehole geophysical records collected by faculty and staff of the University of Waterloo and various consultants working in the region over the past 3 decades. The interpretation was facilitated by calibrating recently cored and geophysically logged boreholes within the region against geophysically logged boreholes lacking high-quality sediment records. The geophysically derived logs will contribute significantly to the modelling process as most of these boreholes were drilled using mud rotary techniques and lack high-quality logs.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.24-1 to 24-4.

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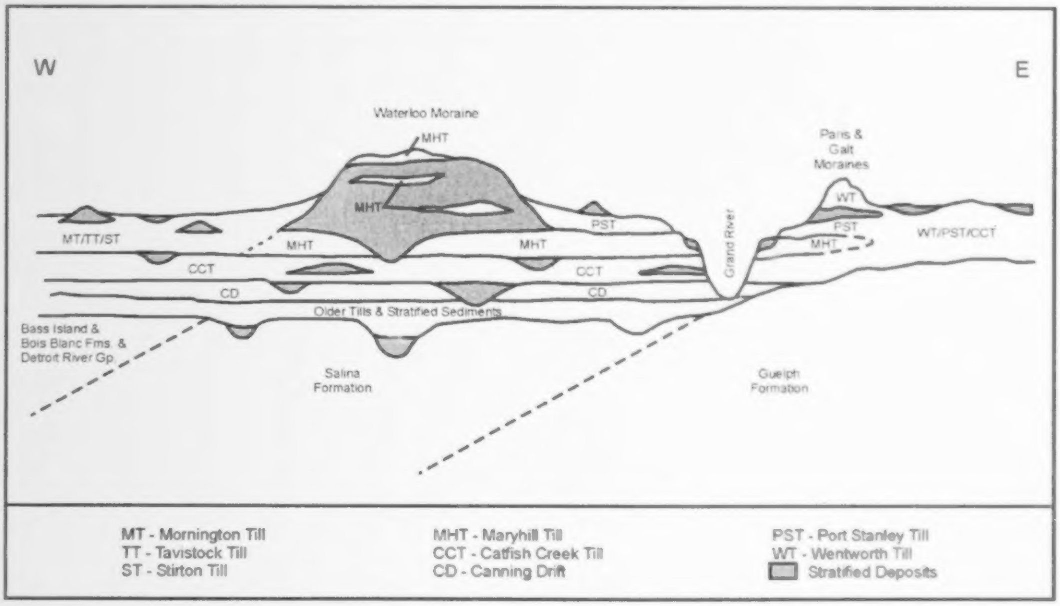
Not surprisingly, most of the databases from which data were derived for the main database were structured differently and utilized terminology inconsistent with that proposed for three-dimensional mapping in southern Ontario. Terminology in each database was standardized in accordance with material codes developed for the seamless Quaternary geology map of southern Ontario (Ontario Geological Survey 2003). Each unique combination of terms was then translated to populate primary, secondary and tertiary material attribute fields in the working database. The original sediment descriptions were retained in a separate field and are available for inspection during the interpretation phase. Locational information was used in conjunction with the provincial digital elevation model (DEM) to derive elevation values for each data point.

During the interpretation phase of the project, it became evident that some of the translations required modification. Cored boreholes in the vicinity of lesser quality water wells drew these issues to the author's attention. In some cases, global changes to the translation were implemented and in other situations, changes were made to the translation on a layer by layer basis.

A CONCEPTUAL GEOLOGIC MODEL

The development of a conceptual geologic model for the interpretation of this data was undertaken following a review of all published information on the Quaternary geology of the Waterloo region. Additional insights were gained by examining all available sediment exposures within the region, relogging of selected archived core, acquisition of seismic reflection and ground penetrating radar data and continuous coring of strategically placed boreholes. The current geologic model contains 8 regionally significant stratigraphic units (Figure 24.1). These include 1) Grand River valley glaciofluvial deposits; 2) upper tills (Wentworth Till, Upper Maryhill Till, Port Stanley Till, Mornington Till, Tavistock Till and Stirton Till); 3) Waterloo Moraine and correlative stratified sediments; 4) Lower Maryhill Till; 5) Catfish Creek Till; 6) Canning Drift; 7) older till and stratified sediments; and 8) bedrock. Further subdivision of these units is achievable at a local scale. In fact, the conceptual hydrostratigraphic model contains 22 units, many of which are discontinuous or restricted to certain parts of the study area.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Detroit River Gp.
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ST - Stirton Till
MHT - Maryhill Till
CCT - Catfish Creek Till
CD - Canning Drift
PST - Port Stanley Till
WT - Wentworth Till
Stratified Deposits

Figure 24.1. Conceptual geologic model for the Regional Municipality of Waterloo. Eight regionally significant lithostratigraphic units are recognized over the Waterloo region.

Not surprisingly, most of the databases from which data were derived for the main database were structured differently and utilized terminology inconsistent with that proposed for three-dimensional mapping in southern Ontario. Terminology in each database was standardized in accordance with material codes developed for the seamless Quaternary geology map of southern Ontario (Ontario Geological Survey 2003). Each unique combination of terms was then translated to populate primary, secondary and tertiary material attribute fields in the working database. The original sediment descriptions were retained in a separate field and are available for inspection during the interpretation phase. Locational information was used in conjunction with the provincial digital elevation model (DEM) to derive elevation values for each data point.

During the interpretation phase of the project, it became evident that some of the translations required modification. Cored boreholes in the vicinity of lesser quality water wells drew these issues to the author's attention. In some cases, global changes to the translation were implemented and in other situations, changes were made to the translation on a layer by layer basis.

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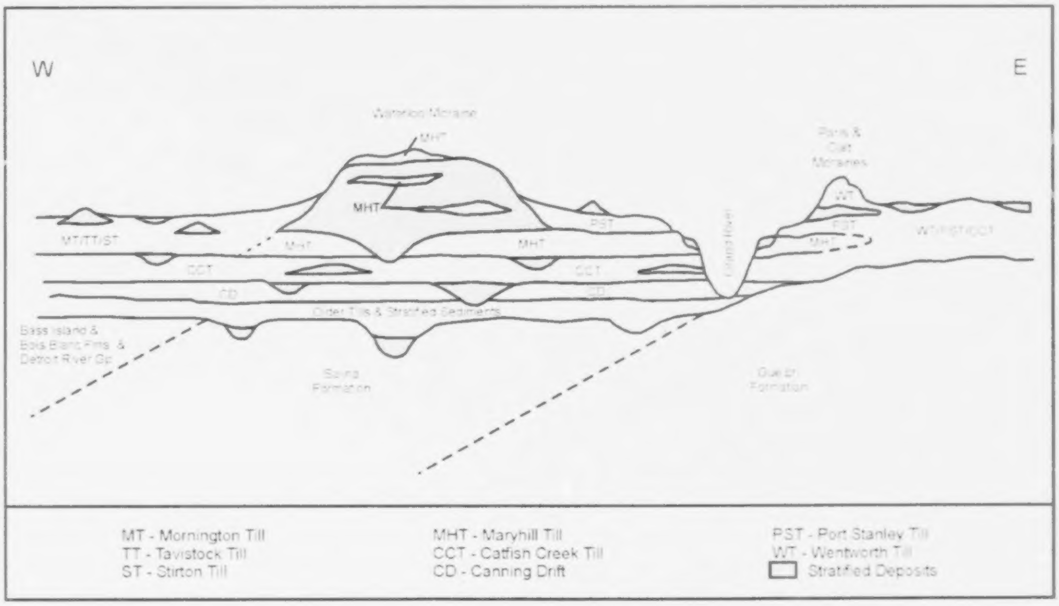
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Older Tills & Stratified Sediments
Bass Island &
Bois Blanc Fms. &
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COLLECTION OF NEW DATA

Programs of seismic reflection and ground-penetrating radar were conducted during the summer and fall of 2003 and were reported on previously (Bajc et al. 2003; Bajc and Karrow 2004). The results of this work have shed some light on the physical properties, geometry and contact relationships of subsurface units. As a follow-up to these programs, a series of 13 continuously cored boreholes were drilled to bedrock during the fall and winter of 2003–2004 and during the fall of 2004. All but one borehole was cased with 2.5-inch inside-diameter PVC piping capped at the base and sealed to surface with bentonite grout to prevent groundwater mixing. Single-level monitors were installed in boreholes containing significant aquifer intersections. These wells will be monitored by staff of the Regional Municipality of Waterloo and the Grand River Conservation Authority.

Geophysical logging of the boreholes was performed under partnership agreements with the Terrain Sciences Division, Geological Survey of Canada and the Department of Earth Sciences, University of Waterloo. Logs performed include natural gamma; inductive conductivity; magnetic susceptibility; gamma–gamma density; temperature–gradient; and compensated neutron. In addition, 2 downhole seismic arrays were applied to all boreholes in order to measure the compressional and shear wave velocity–depth functions as an aid in seismic processing. The magnetic susceptibility of core samples was also measured at 15 cm intervals using a handheld magnetic susceptibility meter. All cores were logged in detail and sampled for combinations of grain size, moisture content (as a proxy to porosity) and matrix carbonate content.

The boreholes, in most cases, displayed a stratigraphic sequence consistent with that developed from this and previous studies. Dense, silt to sand-rich Catfish Creek Till occurs as a widespread marker bed and locally was observed to reach a total thickness of 25 m or more. In all cases, it acts as a relatively impermeable barrier to groundwater flow. Fine-textured glaciolacustrine sediment and associated diamicton, at times displaying a mauve to red colour, was encountered beneath Catfish Creek Till at a number of borehole locations. This unit is tentatively correlated with Canning Drift, which has a broad geographic distribution extending from Beachville in the southwest to Breslau within the region of Waterloo. Canning Drift was encountered beneath organic-bearing sediments of mid-Wisconsinan or Sangamonian age in a borehole drilled on the north campus of the University of Waterloo. Further paleoecological studies are required to determine the age and significance of this occurrence. A weathered zone developed on the upper surface of Canning Till was also encountered in a borehole drilled southwest of the town of Ayr. This paleosol likely records the same non-glacial interval. A number of significant buried aquifers were intersected beneath Catfish Creek drift. Of particular importance is a 30 m thick sequence of sand and gravel that filled in the Wellesley buried valley along the west-central edge of the region. This occurrence emphasizes the importance of buried valleys for hosting future water resources in the region. Most of the region's water supply is obtained from either much younger deposits, as occur in the Waterloo Moraine or from dolostones of the Guelph Formation. The search for future water supplies should focus on buried valleys and older, sub-Catfish aquifers.

DATA INTERPRETATION AND SYNTHESIS

Data interpretation and synthesis is a labour intensive, iterative process that will require the use of high-powered geographic information system (GIS) tools and three-dimensional viewing software. To date, a number of software programs have been utilized in the interpretation and synthesis process. The three-dimensional data are housed in a Microsoft® Access database where it can be easily queried and updated. Preliminary interpretations of the data have been undertaken using ESRI® products such as ArcGIS® and ArcScene® as well as Viewlog®.

Viewlog® is being used initially in the interpretation process to pick formation tops along sections as well as to interpolate surfaces. Its strong link to Microsoft® Access allows for excellent query and live database update functionality. To date, in excess of 35 000 formation top picks have been collected from the study area. Training surfaces were first created using the highest quality, definitive boreholes. Refinements to these surfaces were made using the lower quality MOE water wells records. This process does not come without its challenges. The interpreter must look for patterns in the data that are repeatable and geologically valid. In many cases, the water well records are simply rejected or overlooked if their integrity is in question.

Viewlog® is being used to krig surfaces independently and to apply constraining rules that ensure stratigraphic integrity. The OGS is also currently evaluating higher powered, three-dimensional modelling software to assist with the tasks of modelling more complex subsurface units such as lenses and pinchouts and for the creation of block solid models for volumetric and hydrogeologic flow modelling. Following the construction of a three-dimensional geologic model, activities will shift and focus on the development of both technical and "user-friendly" derivative products that will assist with policy-making decisions and resolution of land use issues.

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25. Project Unit 02-019. Groundwater Resource Projects (GRPs)

P. Sarvas[1], R.I. Kelly[1] and C.L. Baker[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Under the province's Clean Water Strategy, the Sedimentary Geoscience Section (SGS) of the Ontario Geological Survey (OGS) has established a program of groundwater mapping (Kelly 2002; Kelly, Sarvas and Baker 2003). The major objectives of the program are to delineate and characterize the major groundwater aquifers in Ontario. The program will generate information on the geological characteristics of the aquifers and their surroundings. This information will be valuable in such initiatives as watershed management, land use planning and wellhead protection. It is envisioned that the program will also provide technical data to help support the development of source water protection plans in Ontario's watersheds.

A number of projects have been initiated under the groundwater mapping program. These include: 1) completion of a geographic information system (GIS)-based, "seamless" map of the Quaternary geology for southern Ontario; 2) subsurface three-dimensional (3-D) mapping of the Waterloo and Oro moraines in southern Ontario; 3) characterization of fractured Paleozoic in areas of thin drift cover for nutrient management; 4) data management and modelling for collected groundwater program information and data; and 5) completion of a series of watershed-based groundwater resource projects (or GRPs). The latter initiative is the subject of this article.

BACKGROUND

As part of an integrated program submission within the 2001–2002 fiscal year, the ministries of Northern Development and Mines (MNDM), Environment (MOE), Natural Resources (MNR) and Agriculture and Food (OMAF) proposed a multi-year strategy to address issues facing drinking water in Ontario. Initial funding was approved for MNDM's "Aquifer Mapping and Susceptibility to Contamination" component of the program in July 2001. For fiscal years 2002–2003, 2003–2004 and 2004–2005, additional funding was approved to continue MNDM's groundwater mapping program. This mapping program, delivered through the OGS, contributes to the 4 pillars of the Clean Water Strategy, namely, groundwater information, source protection, managing water taking and reducing risks.

GROUNDWATER RESOURCE PROJECTS

For approximately 3 million people in Ontario, groundwater is a primary source of water (MOE 2004). Groundwater is particularly important in rural communities, where it is often the sole source of drinking water for domestic residences and agricultural operations. Groundwater also provides baseflow to streams and wetlands within a watershed, thereby helping to support aquatic ecosystems, and is used in agricultural, commercial and industrial operations.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.25-1 to 25-4.

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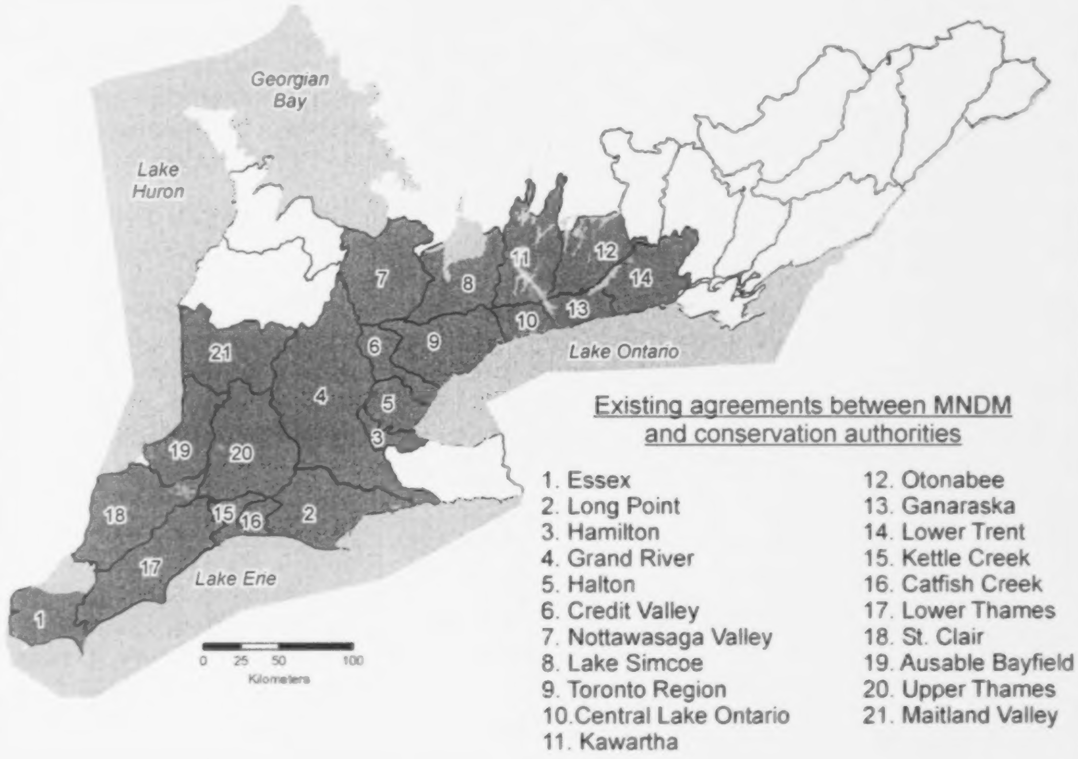
The OGS has entered into agreements with many of Ontario's conservation authorities to complete Groundwater Resource Projects (or GRPs) in their watershed areas. The principal objective of GRPs is to provide geoscience information on the watershed's groundwater systems. Presently, GRPs cover most of southwestern and south-central Ontario (Figure 25.1). The projects are in various stages of completion (Table 25.1), and reports on 2 GRPs (Central Lake Ontario and Essex Region) are in publication.

The GRP program recognized that groundwater systems are much better understood in some parts of Ontario than in others. Recent intensive studies of the Oak Ridges Moraine, for example, have led to the development of complex three-dimensional geological and stratigraphic models (Sharpe et al. 1999; Logan, Russell and Sharpe 2001; Holysh and Davies 2003). Elsewhere, the extent and characteristics of regional aquifers are poorly understood and are only beginning to be studied and documented. Each of the GRPs is tailored to address the most crucial geological information requirements of its watershed. GRPs include investigations of overburden types and textures, the three-dimensional extent of sand-and-gravel deposits and low-permeability layers, bedrock surface topography, lithology and bedrock structures, water table and potentiometric surfaces and ambient groundwater geochemistry. Methodologies include data compilations followed by map and cross-section generation, borehole logging and monitoring well installation, downhole and regional geophysical profiling, conceptual and computer-assisted aquifer modelling and groundwater sampling and analysis.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Kilometers
Existing agreements between MNDM and conservation authorities
1. Essex
2. Long Point
3. Hamilton
4. Grand River
5. Halton
6. Credit Valley
7. Nottawasaga Valley
8. Lake Simcoe
9. Toronto Region
10. Central Lake Ontario
11. Kawartha
12. Otonabee
13. Ganaraska
14. Lower Trent
15. Kettle Creek
16. Catfish Creek
17. Lower Thames
18. St. Clair
19. Ausable Bayfield
20. Upper Thames
21. Maitland Valley

Figure 25.1. Locations of conservation authorities with existing Groundwater Resource Project (GRP) agreements with the Ministry of Northern Development and Mines.

Table 25.1. Groundwater Resource Projects (GRPs) funded by MNDM, showing the partnerships involved in the projects and the estimated completion date for the field components of the the projects (*see also* Figure 25.1).

Project Name	Partners	Estimated Completion Date of Field Work
Central Lake Ontario groundwater resource inventory	Central Lake Ontario Conservation Authority	Completed
Essex region groundwater resource inventory*	Essex Region Conservation Authority	Completed
Long Point region groundwater resource inventory*	Long Point Region Conservation Authority	Fall 2004
Grand River groundwater resource modelling	Grand River Conservation Authority	2005
Conservation Authority Moraine Coalition groundwater resource studies	Credit Valley, Nottawasaga Valley, Lake Simcoe Region, Toronto Region, Central Lake Ontario, Kawartha, Otonabee Region, Ganaraska and Lower Trent conservation authorities	2005
Buried bedrock valley study	Lake Simcoe Region Conservation Authority	2005
Hamilton groundwater resource inventory*	Hamilton Conservation Authority	2005
Catfish Creek–Kettle Creek groundwater resource inventory*	Catfish Creek and Kettle Creek conservation authorities	2005
Southwestern Ontario three-dimensional groundwater modelling**	Ausable Bayfield, Essex, Lower Thames Valley, Maitland Valley, St. Clair and Upper Thames River conservation authorities	2005
Upper Thames River downhole gamma-ray logging	Upper Thames River Conservation Authority	2005
Ausable Bayfield sinkhole study	Ausable Bayfield Conservation Authority	2005
North Lambton groundwater study***	Ausable Bayfield Conservation Authority	2005

* technical assistance provided by Grand River Conservation Authority;

** Upper Thames River Conservation Authority lead agency;

*** technical assistance provided by Maitland Valley Conservation Authority

In June 2004, MOE released a draft "Drinking Water Source Protection Act". An integral component of the Act is the establishment of Source Protection Plans for all of Ontario's watersheds based on the gathering and interpretation of technical data. The Act also requires the continual monitoring and amendment of Source Protection Plans, including the amendment of Plans based on the introduction of more, or more reliable, technical data. It is envisioned that GRPs will provide important technical data to use in both the establishment and the amendment of Source Protection Plans.

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26. Project Unit 04-027. Catfish Creek–Kettle Creek Conservation Authorities Groundwater Resource Project

S. Strynatka[1], J. Pitcher[1] and P. Dragunas[2]

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INTRODUCTION

With a growing population and increase in industrialization, there is an escalating demand on Ontario's groundwater to supply water to both private residences and provide water for agricultural, industrial and other uses. Therefore, it has become critical to identify and protect regional aquifers and aquitards as well as areas of significant groundwater recharge.

Under the Ontario Geological Survey's (OGS) Groundwater Resource Projects (GRPs) program and in conjunction with the Catfish Creek, Kettle Creek and Grand River conservation authorities, a groundwater mapping program is currently underway within the Catfish and Kettle Creek watersheds. Both watershed are located in southwestern Ontario (Figure 26.1). The data collected from this project will assist in the support of watershed management and the development of sound land-use planning and source protection strategies (Kelly, Sarvas and Baker 2003).

The purpose of this study is to delineate and characterize, on a two-dimensional basis, the groundwater resources of the Catfish Creek and Kettle Creek watersheds, as well as a 5 km 'buffer zone' around the watersheds. The completion of two-dimensional groundwater and aquifer mapping is a first step towards mapping the three-dimensional subsurface geology of Ontario in a standardized and correlatable manner. Through analysis of the Ministry of Environment's (MOE) Water Well Information System (WWIS) database for water wells, the Ontario Oil, Gas and Salt Resources database for oil and gas well records, and previously completed studies from public and private sources, interpretations can be made to better understand the subsurface geology and hydrogeology of the 2 watersheds.

BACKGROUND

The Catfish and Kettle Creek watersheds, located adjacent to each other in southwestern Ontario, both drain into Lake Erie (*see* Figure 26.1). The Catfish Creek watershed drains an area of 490 km^2, whereas the Kettle Creek watershed drains 500 km^2. The combined population of both watersheds is approximately 193 450 people (Statistics Canada 2001). Within the study area, the larger urban centres include Aylmer, Belmont, Union, Port Stanley and St. Thomas. The study area also includes a portion of the city of London. Approximately 86.9% of the area's population is urban (approximately 67% of which can be attributed to the city of London) and 13.1% is rural.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.26-1 to 26-5.

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WATER WELL USAGE

Within the study area, the MOE WWIS database indicates the presence of approximately 7000 wells. Of these wells, 90% are completed within the overburden and the remaining 10% within bedrock. The primary well water use within the study area is for domestic purposes (66%).

Qualitative water quality, as assessed by the well drillers at the time of well construction, is also contained within the MOE WWIS database. Of the wells completed in overburden, 97% were reported to contain fresh water and 1% were reported as sulphurous. In comparison, 51% of the bedrock wells were reported to draw fresh water, 41% were reported as having a sulphur problem and 3% were observed to have a high mineral content.

SURFICIAL AND BEDROCK GEOLOGY

Two bedrock formations, the Devonian Marcellus and Dundee formations, underlie the study area. The Marcellus Formation stretches in an east-trending direction along the southern portion of the study area. This formation is characterized by black, organic-rich shale with minor, thin, impure carbonate beds. It ranges up to 12 m in thickness and conformably overlies the Dundee Formation (Johnson et al. 1992). The Dundee Formation consists of brown, fossiliferous limestone with chert nodules and bituminous partings. It is generally in the order of 25 to 45 m in thickness (Johnson et al. 1992). A small portion of the northwest corner of the study area is underlain by the Devonian Hamilton Group, which consists mostly of mudstone and shale with thin, laterally persistent carbonate strata (Johnson et al. 1992).

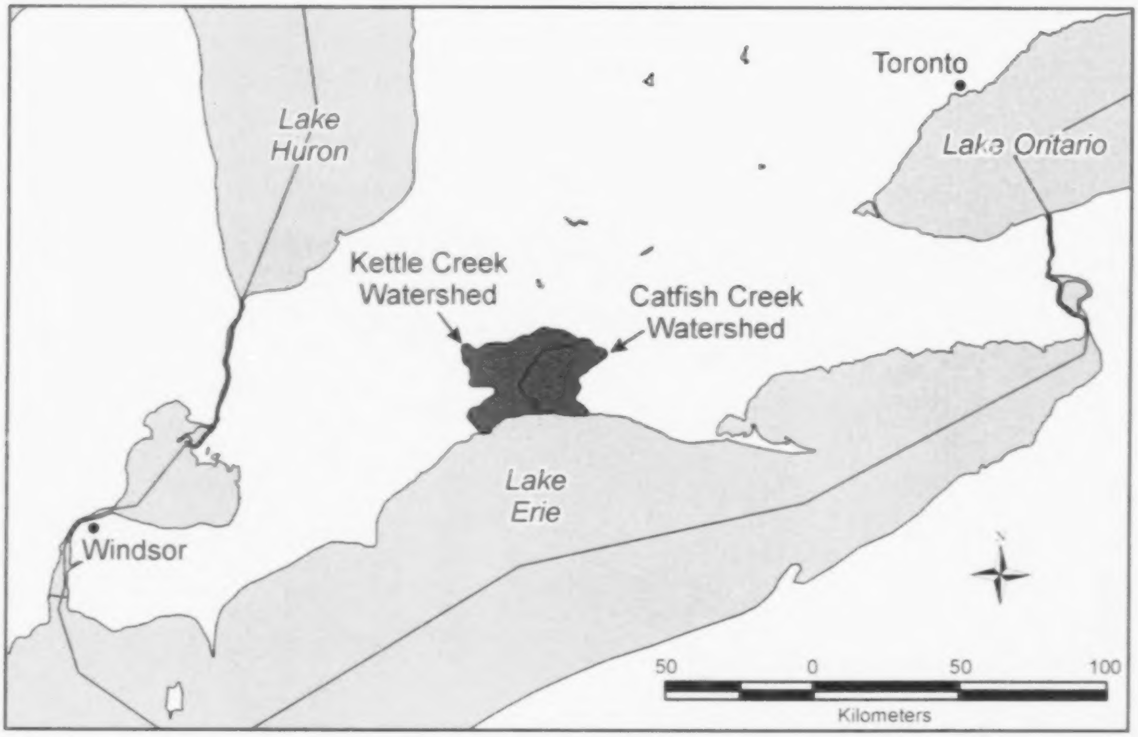
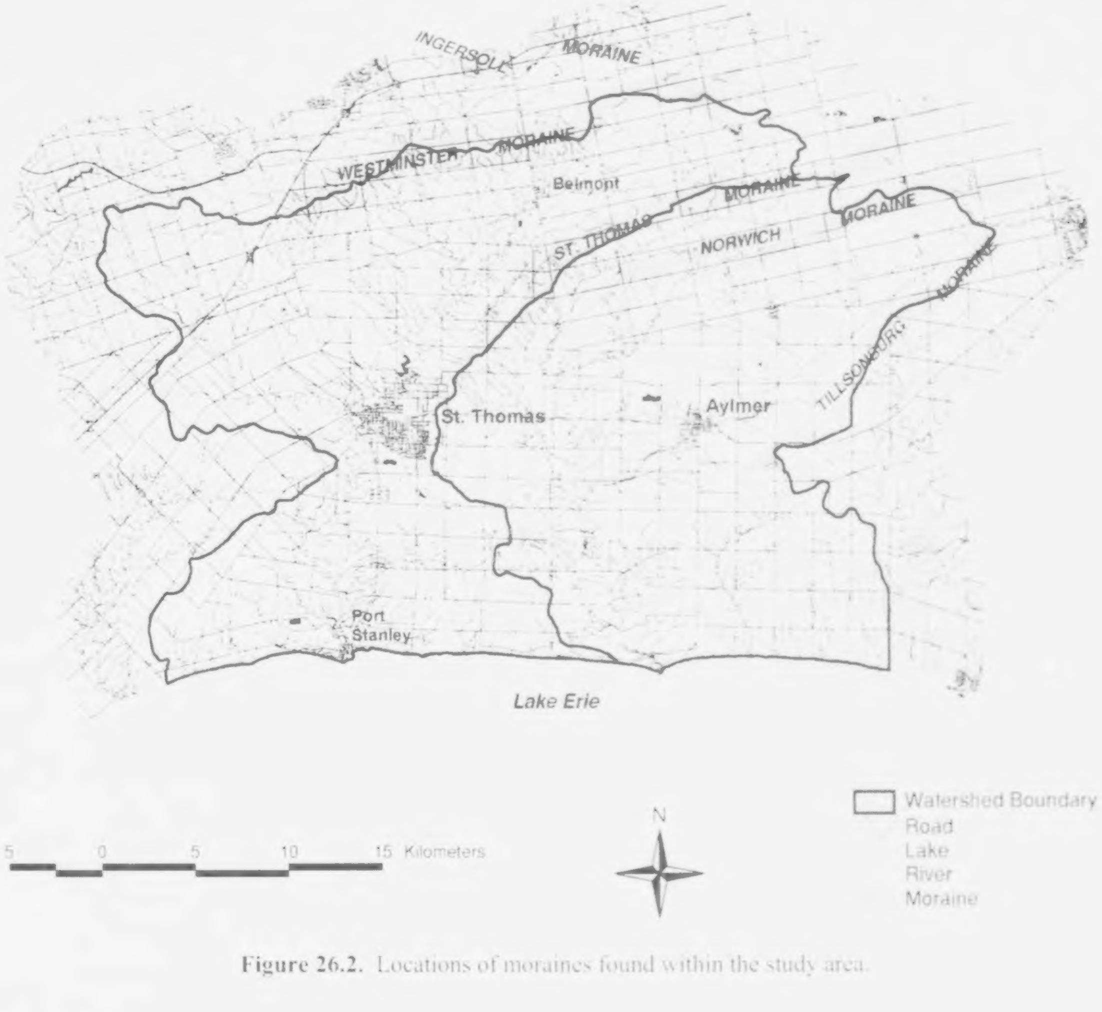


Figure 26.1. Locations of Kettle Creek and Catfish Creek watersheds in southwestern Ontario.

The primary surficial materials of the study area are shown in the geographic information system (GIS)-based *Surficial Geology of Southern Ontario* map (Ontario Geological Survey 2003). The surficial overburden in the northern half of the study area is predominantly Port Stanley Till. This till unit has been previously characterized as strongly calcareous with a silt to silty clay matrix and a moderate to low clast content that decreases southward toward Lake Erie (Barnett 1992). Port Stanley Till commonly occurs as ground moraine and end moraines up to 25 m thick (Dillon Consulting Limited 2004).

Associated with the deposition of Port Stanley Till are 5 southwest-trending moraines (Westminster, St. Thomas, Norwich, Tillsonburg and Ingersoll) (Figure 26.2). These have been classified as end moraines related to either minor re-advances or marking the standstill of the Erie–Ontario ice lobe of the Laurentide Ice Sheet (Barnett 1992). The Westminster moraine, which forms the drainage divide for a portion of the northern boundary of the Kettle Creek watershed, is composed primarily of clay and is approximately 15 m high and 2.5 km wide (Chapman and Putman 1984). Extending for almost 100 km, the St. Thomas moraine forms the northern portion of the drainage divide between the Catfish and Kettle Creek watersheds. The Norwich moraine, located within the Catfish Creek watershed, is split into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Lake
River
Moraine

Figure 26.2. Locations of moraines found within the study area.

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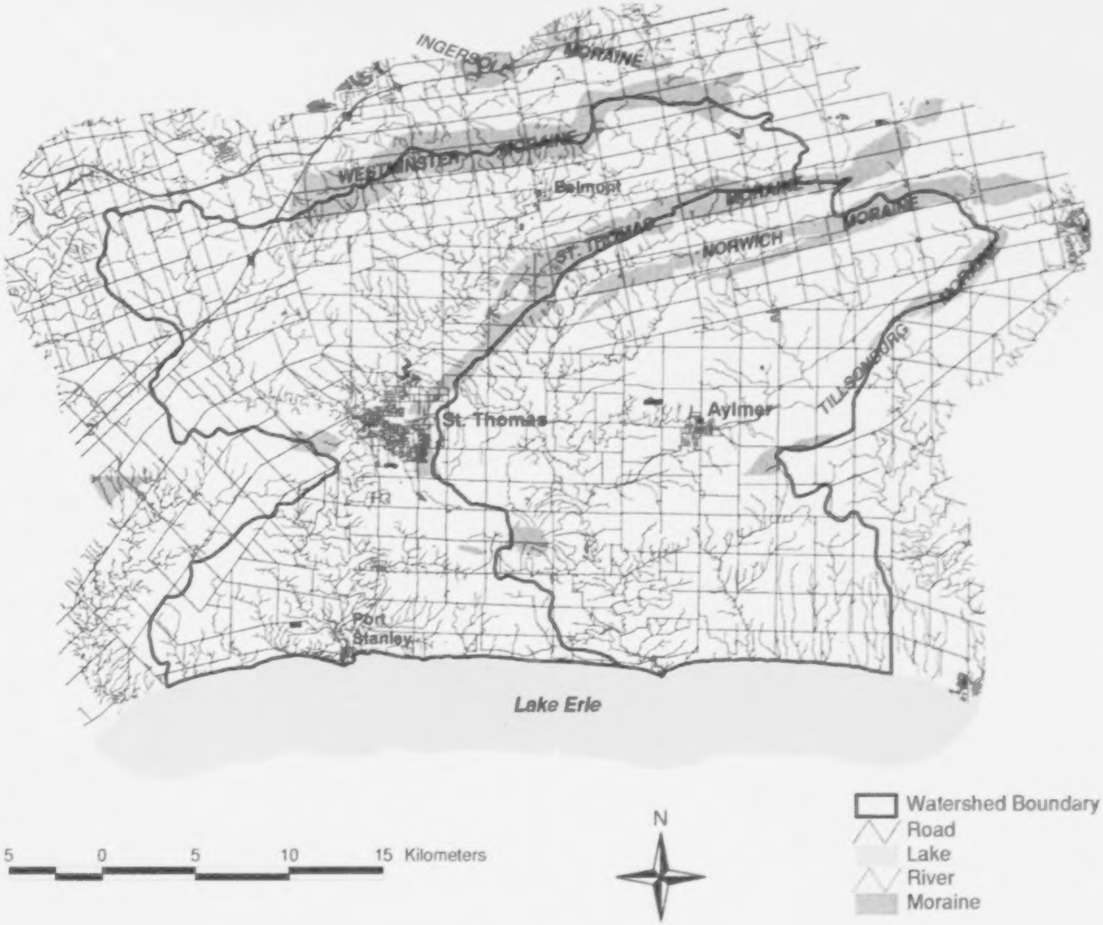
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Port Stanley
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5 0 5 10 15 Kilometers
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Watershed Boundary
Road
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River
Moraine

Figure 26.2. Locations of moraines found within the study area.

2 branches separated by a tributary of Catfish Creek. The Tillsonburg moraine marks a portion of the watershed boundary along the east side of the Catfish Creek watershed, and the Ingersoll moraine is found within the 5 km buffer zone, located north of the Westminster moraine and along the northern boundary of the study area.

The surficial geology in the southern half of the study area (primarily sand and silt) is characterized largely by 2 types of glaciolacustrine deposits; alluvial nearshore and/or beach deposits and deeper water basinal deposits. The nearshore deposits (part of the Norfolk Sand Plain) occur as fine- to coarse-grained, northeast-trending sand deposits across the southern part of the study area. These beach deposits are unconfined aquifers, providing a groundwater supply to public and private residences in the area (Chapman and Putnam 1984; Dillon Consulting Limited 2004). Silty to clayey deeper water basinal deposits, which occur in tandem with the nearshore sand deposits, are also found throughout the southern extent of the study area and are prominent southwest of Kettle Creek.

REGIONAL GROUNDWATER MAPPING

It is a primary goal of this project to develop a robust data set for the study area prior to the start of groundwater mapping. The creation of this augmented data set, based upon the existing MOE WWIS database, is a three-part process consisting of the following components:

- The current WWIS database for the study area contains 1492 wells (representing approximately 20% of the database) with unreliable location co-ordinates (as identified by MOE criteria). To verify or correct these co-ordinates, a field location program will locate these wells and obtain accurate UTM positions using a global positioning system (GPS) unit.
- In addition to using the WWIS database, records from oil and gas wells drilled in the study area have been obtained. These records contain accurate data on UTM and elevation co-ordinates, depth to bedrock and geological units, and will be included in the database.
- To further increase the robustness of the database, efforts are being made to obtain borehole data from sources such as landfills and aggregate pits in the area. Data obtained from these holes are generally considered to be of higher quality because of their accurate UTM locations and because a qualified geoscientist generally logs the boreholes.

Upon completion of the updated database, mapping the subsurface geology and hydrogeology of the study area will be carried out in 3 phases:

- The first phase will assess groundwater use issues within the study area. Groundwater use issues will be addressed through the development and interpretation of 'point' data. This will include the generation of maps that, directly drawing upon data in the updated WWIS database, will show the distribution of groundwater uses (i.e., domestic, agricultural, industrial), the distribution of overburden and bedrock wells, highlight water quality issues and the specific capacity of individual wells.
- The second phase will consist of the development of geological and hydrogeological two-dimensional 'surfaces'. This will be completed through the characterization of the geological and hydrogeological subsurfaces and the development of interpolated (kriged) surfaces from point data contained in the WWIS database, oil and gas well logs and other borehole data. Surfaces characterizing the subsurface geology will include overburden thickness, total sand and gravel thickness and bedrock topography. The regional hydrogeology of the study area will be characterized through the development of maps showing the water table surface, potentiometric surface, potential surficial discharge areas and vertical hydraulic gradients.

- A third phase of the groundwater mapping will consist of the development of aquifer vulnerability maps. On a preliminary basis, this will include maps showing the depth to bedrock, the depth to the first sand and gravel aquifer and an overall aquifer vulnerability map combining the depth to bedrock and depth to first aquifer maps. The aquifer vulnerability maps are meant to be used in a land-use planning capacity, but will require field verification for site-specific studies.

CURRENT ACTIVITIES

In the spring of 2004, Catfish Creek Conservation Authority hired a hydrogeological technician to carry out the field program to locate wells from the WWIS database with poor location information, update the database with additional high-quality borehole data, perform water well data analyses in a GIS environment and prepare regional-scale groundwater maps. The Grand River Conservation Authority is providing GIS and hydrogeological technical expertise for the interpretation of the regional hydrogeological maps and preparation of the final report. The field program is currently underway and the groundwater mapping component of the study is expected to begin in the latter part of 2004.

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27. Project Unit 03-020. Groundwater Resource Projects Across the Oak Ridges Moraine

S.D. Davies[1] **and S. Holysh**[1]

[1]Conservation Authorities Moraine Coalition

INTRODUCTION

This article provides an update on work undertaken over the past year across the Oak Ridges Moraine (ORM) area in support of the Ontario Geological Survey's Groundwater Resource Project (GRP) program. The goal of this program is to generate a series of regional-scale interpretative maps and reports that can be used to better understand the groundwater systems within individual watersheds (Kelly, Sarvas and Baker 2003). Additional background materials related to the current project can be found in Holysh and Davies (2003).

BACKGROUND

The OGS has partnered with the 9 conservation authorities comprising the Conservation Authorities Moraine Coalition (CAMC) to complete a series of groundwater resource projects (Figure 27.1). The objective of the partnership is to continue work previously initiated across the ORM with respect to database management and geological and numerical groundwater modelling (Earthfx Incorporated 2004; Gerrie et al. 2003; Holysh et al. 2003; Kassenaar, Holysh and Gerber 2003; Wexler et al. 2003).

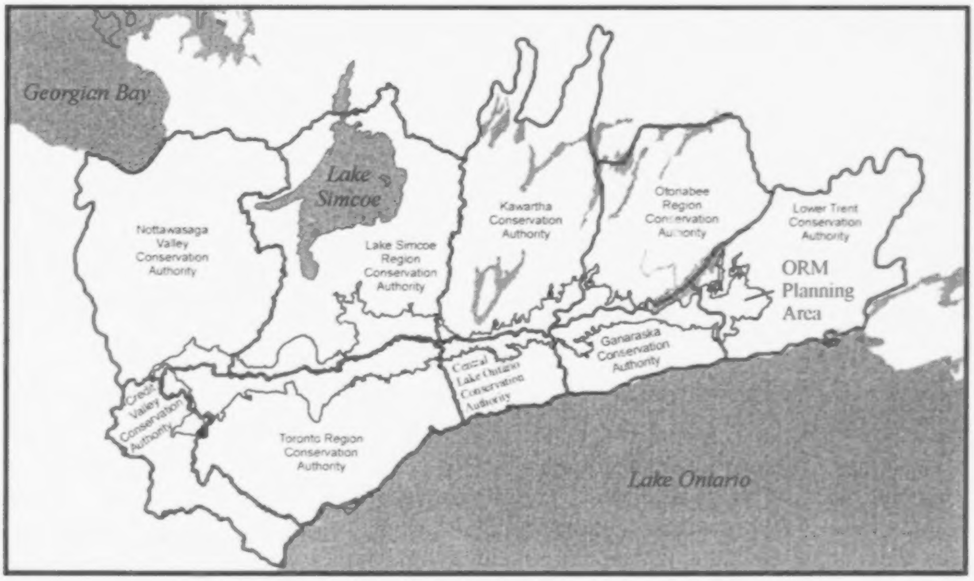
Georgian Bay
Lake Simcoe
Nottawasaga Valley Conservation Authority
Lake Simcoe Region Conservation Authority
Kawartha Conservation Authority
Otonabee Region Conservation Authority
Lower Trent Conservation Authority
ORM Planning Area
Ganaraska Conservation Authority
Central Lake Ontario Conservation Authority
Credit Valley Conservation Authority
Toronto Region Conservation Authority
Lake Ontario

Figure 27.1. Location of watersheds studied and conservation authorities involved in the Conservation Authorities Moraine Coalition (CAMC) partnership.

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Ontario Geological Survey, Open File Report 6145, p.27-1 to 27-8.

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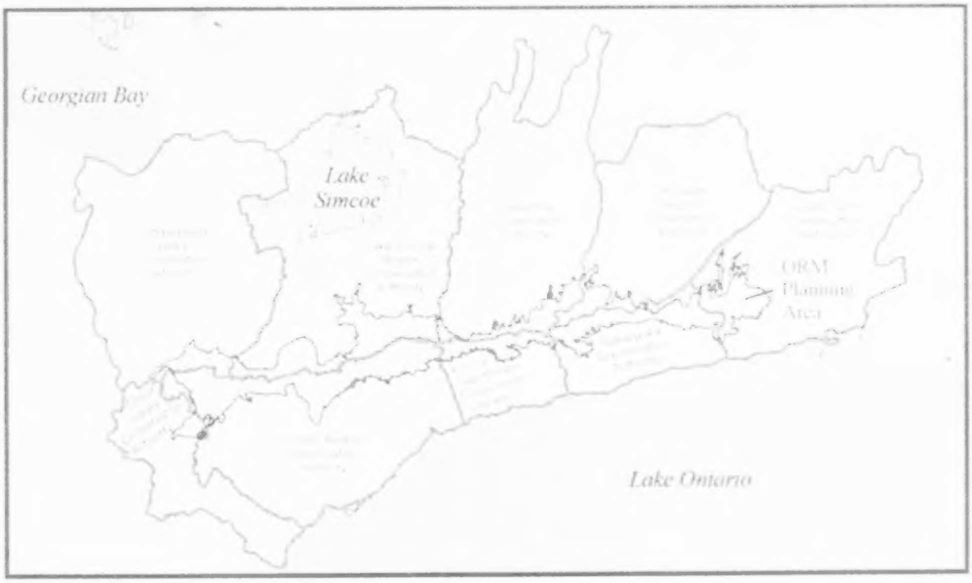

Figure 27.1. Location of watersheds studied and conservation authorities involved in the Conservation Authorities Moraine Coalition (CAMC) partnership.

Summary of Field Work and Other Activities 2004
Ontario Geological Survey, Open File Report 6145, p.27-1 to 27-8.

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Aquifer delineation is difficult to carry out in the ORM complex and in the buried-valley aquifers that underlie it or occur across this region. Accordingly, high-quality data including seismic profiles, continuously cored boreholes and borehole geophysical data are being collected across this region (e.g., Pullan et al. 2004). The Geological Survey of Canada (GSC) is providing partnership support with respect to some of these data and particularly with respect to buried-valley aquifers (e.g., Russell et al. 2004a, 2004b; Sharpe et al. 2004). A number of strategic initiatives are ongoing to help interpret the geology and hydrogeology of these areas in support of water resource assessment and management.

2004 FIELD PROGRAM

Some of the key projects ongoing in 2004 include

- a seismic survey and data analysis of a deep bedrock valley (discovered during a 2001 borehole drilling program) in the Caledon East area (Figures 27.2, 27.3 and 27.4)) (Pullan et al. 2004; Russell et al. 2004a, 2004b);
- drilling of a deep, high-quality borehole through ORM sediments south of Rice Lake in the Lower Trent Conservation Authority area (Figure 27.5);
- test seismic spreads just west of Port Perry to investigate a possible alternative water source for Port Perry;
- organization of a field trip for planners and technical staff from the conservation authorities and the partnered municipalities; and
- ongoing refinement and interpretation of the sediment hydrostratigraphy in the regional municipalities of York, Peel and Durham and in the City of Toronto (Earthfx Incorporated 2004; Kassenaar, Holysh and Gerber 2003; Wexler et al. 2003).

Caledon East Seismic Survey

The seismic survey completed in the Caledon East area consisted of 3 lines, approximately 3 to 4 km long, oriented roughly perpendicular to the orientation of the interpreted bedrock valley (*see* Figure 27.2).

The seismic survey was completed by Geophysical Applications (GAPs) of Guelph, Ontario. The GSC is contributing technical input regarding the geological context and interpretation of the seismic profiles (*see* Figure 27.3). The seismic results indicate the presence of a deep bedrock valley that is approximately 70 m deeper than the surrounding bedrock surface topography and is up to 1.5 km wide. Data from a deep borehole on Heart Lake Road (CVC-1; *see* Figure 27.2) indicates the presence of a deeply buried sand-and-gravel aquifer, approximately 30 m thick, overlying bedrock. In the seismic line profile that passes nearest the borehole location (line #1; *see* Figure 27.2), the aquifer's signature is interpreted to have a high-amplitude, hummocky signature (seismic facies #3; *see* legend in Figure 27.3). This coarse sand to gravel facies is interpreted to be over 100 m thick in the profile of seismic line #2 along Mountainview Road and is also interpreted to be present in the profile of seismic line #3 along Humber Station Road (*see* Figure 27.3). In the profiles of both seismic lines #1 and #2 both sides of the bedrock valley system can be observed. In the profile of line #3, however, the entire bedrock valley was not transected and only the southern slope of the valley is evident.

These results suggest the presence of a thick sand-and-gravel aquifer that is continuous along the base of the bedrock valley system. This aquifer may have potential as a municipal drinking water source. Exploratory drilling along Mountainview Road is highly recommended as a follow-up initiative.

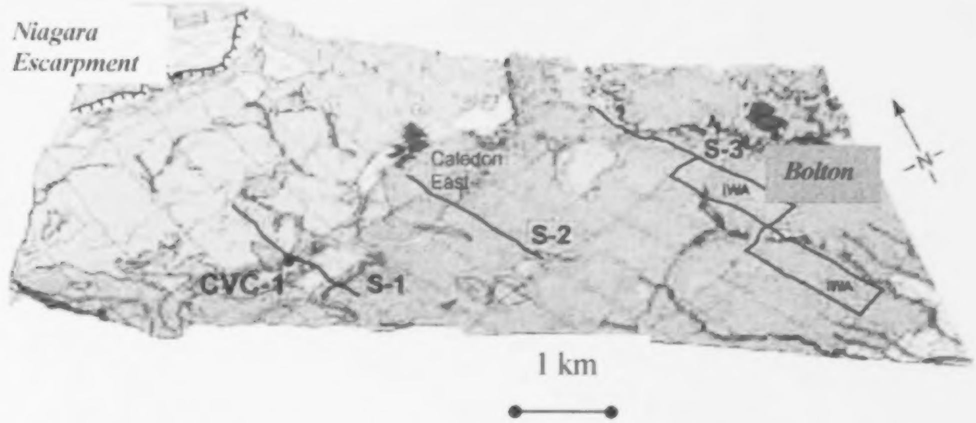
Niagara
Escarpment
Caledon
East
S-3
Bolton
N
IWA
S-2
CVC-1
S-1
IWA
1 km

Figure 27.2. Location of the deep borehole (CVC-1) and 3 seismic lines (S-1 through S-3) completed for the Caledon East seismic survey (*from* Russell et al. 2004a).

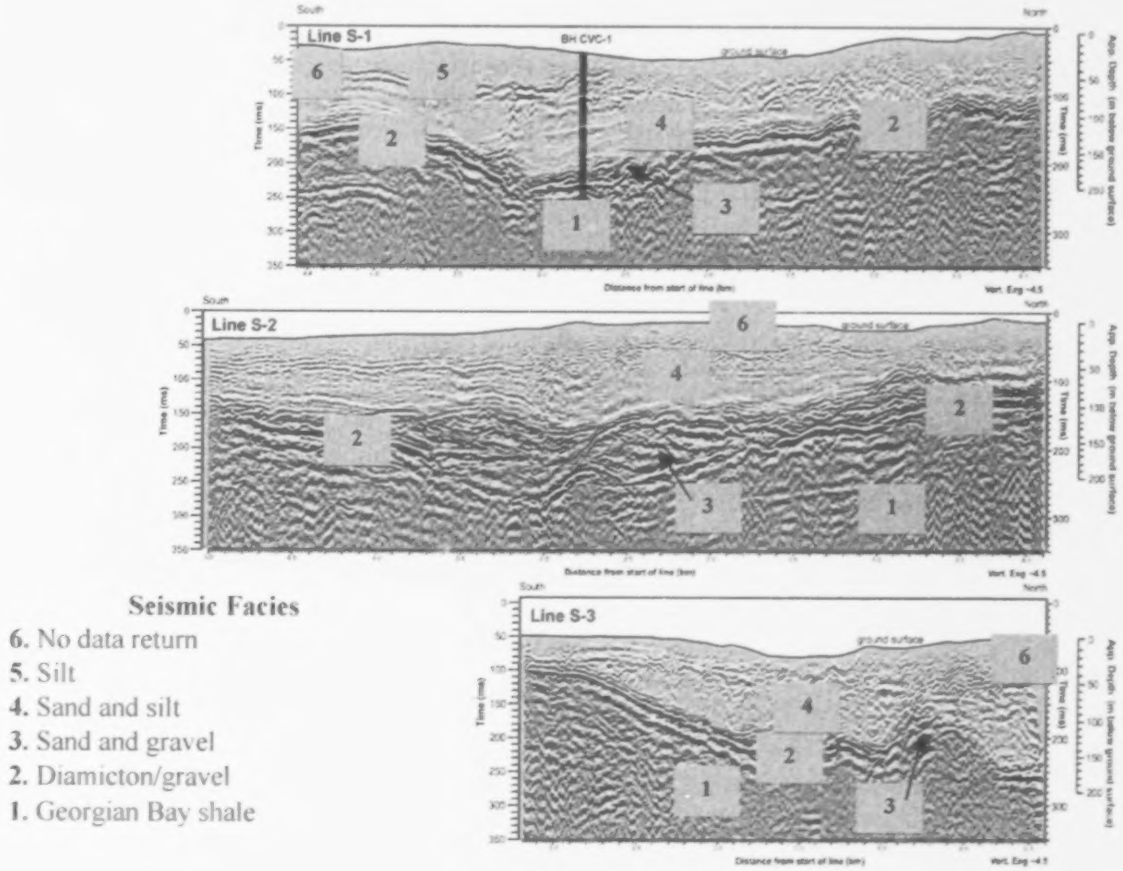
South
North
Line S-1
BH CVC-1
ground surface
6
5
4
2
2
1
3
Time (ms)
Time (ms)
App. Depth (m below ground surface)
Distance from start of line (km)
Vert. Exg ~4.5
South
North
Line S-2
ground surface
6
4
2
2
3
1
Time (ms)
Time (ms)
App. Depth (m below ground surface)
Distance from start of line (km)
Vert. Exg ~4.5
Seismic Facies
6. No data return
5. Silt
4. Sand and silt
3. Sand and gravel
2. Diamicton/gravel
1. Georgian Bay shale
South
North
Line S-3
ground surface
6
4
2
1
3
Time (ms)
Time (ms)
App. Depth (m below ground surface)
Distance from start of line (km)
Vert. Exg ~4.5

Figure 27.3. Facies interpretations of the seismic profiles of lines S-1, S-2 and S-3 of the Caledon East seismic survey (*from* Russell et al. 2004a).

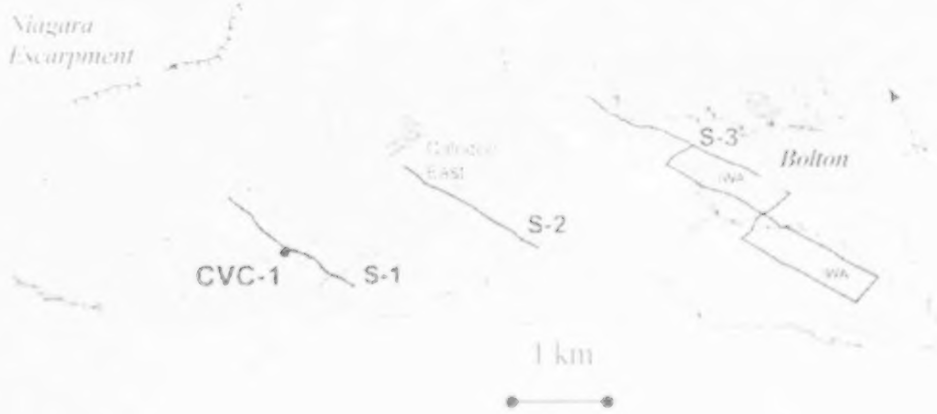
Niagara
Escarpment
Caledon
East
S-3
Bolton
S-2
CVC-1
S-1
1 km

Figure 27.2: Location of the deep borehole (CVC-1) and 3 seismic lines (S-1 through S-3) completed for the Caledon East seismic survey (from Russell et al. 2004a).

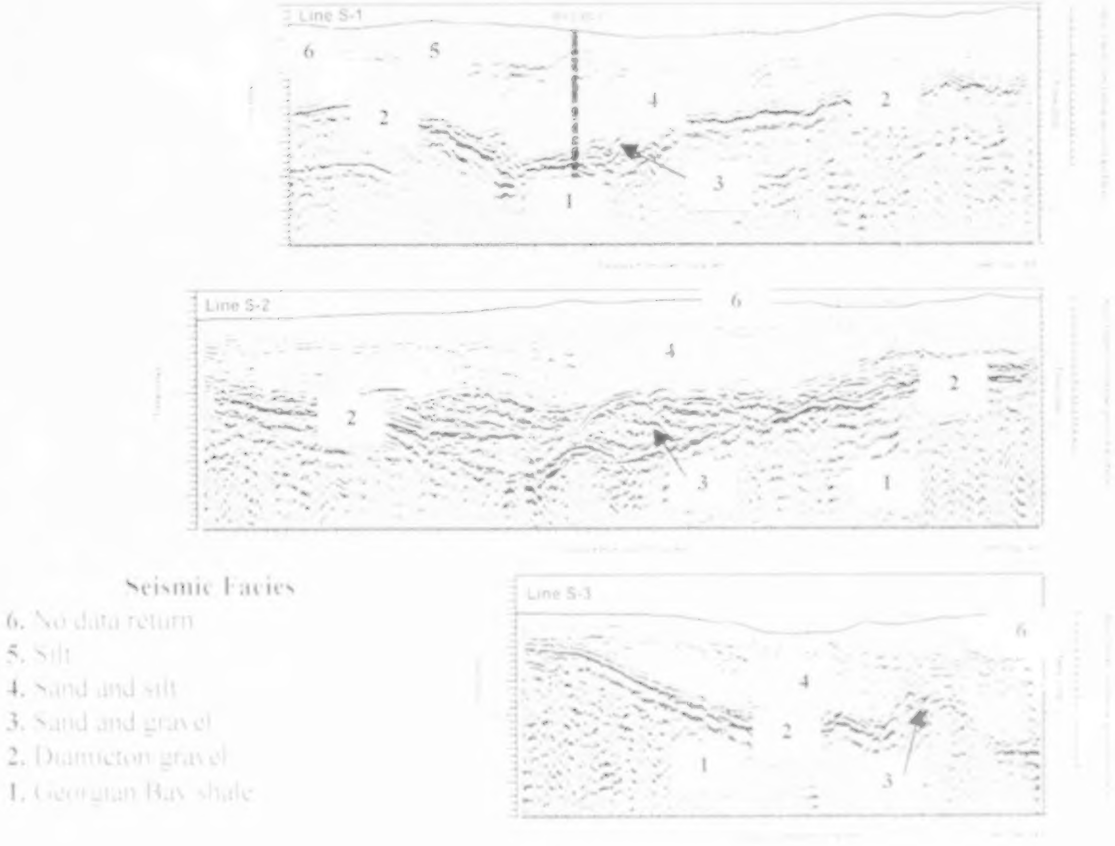
Line S-1
6
5
2
4
2
3
1
Line S-2
6
4
2
2
3
1
Seismic Facies
6. No data return
5. Silt
4. Sand and silt
3. Sand and gravel
2. Diamicton gravel
1. Georgian Bay shale
Line S-3
6
4
2
1
3

Figure 27.3. Facies interpretation of the seismic profiles of lines S-1, S-2 and S-3. [illegible] Russell et al. 2004a).

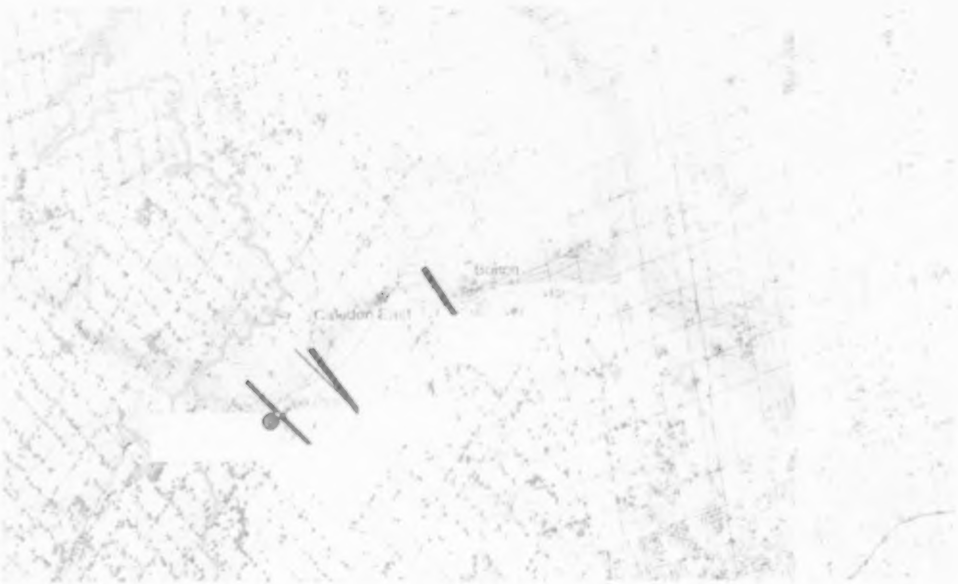

Figure 27.4. Interpolated bedrock topography in the area of the Caledon East seismic survey. The approximate locations of the seismic lines S-1, S2 and S-3 are also shown. CVC-ORM1 is a deep borehole. Geological information from this borehole was correlated with the seismic profiles. The small black dots indicate the locations of water wells that intersected bedrock. Note the sparcity of these types of water wells within the interpreted valley. This interpreted map was produced under the assumption that valleys are connected as part of a connected subaerial drainage model.

Rice Lake
Cobourg

Figure 27.5. Location of the exploratory borehole [illegible] CAMC-YPDT-Rice Lake-1 on the Rice Lake [illegible] CAMC-YPDT-Rice Lake [illegible]

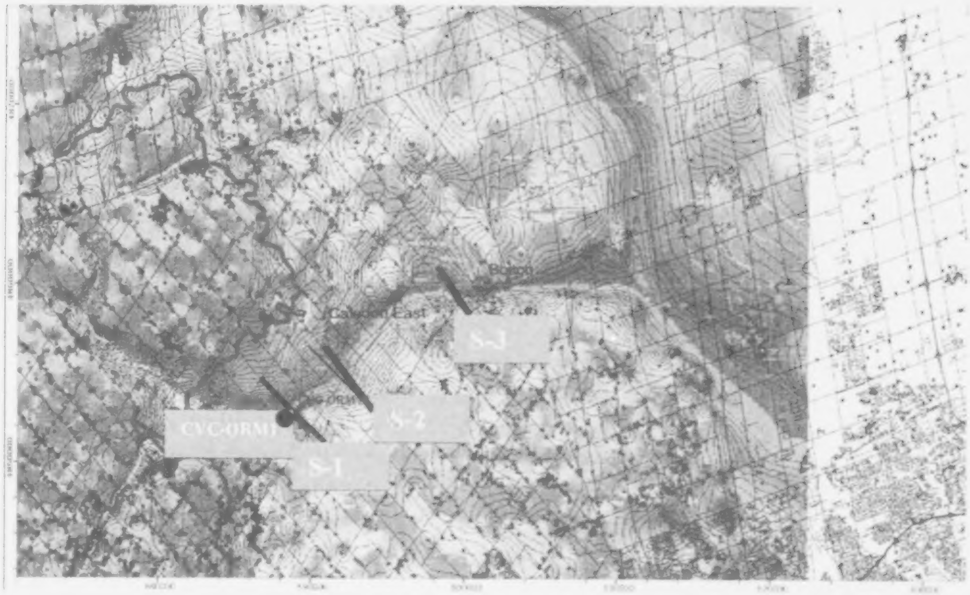
Bolton
Caledon East
S-3
S-2
S-1
CVC-ORM1

Figure 27.4. Interpolated bedrock topography in the area of the Caledon East seismic survey. The approximate locations of the seismic lines S-1, S2 and S-3 are also shown. CVC-ORM1 is a deep borehole. Geological information from this borehole was correlated with the seismic profiles. The small black dots indicate the locations of water wells that intersected bedrock. Note the sparcity of these types of water wells within the interpreted valley. This interpreted map was produced under the assumption that valleys are connected as part of a connected subaerial drainage model.

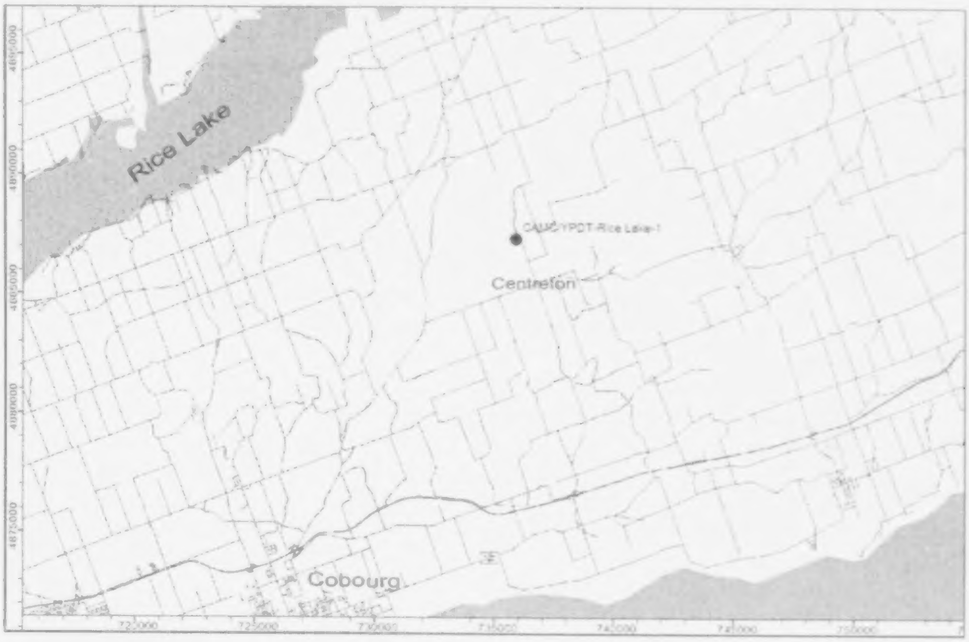
4895000
4890000
4885000
4880000
4875000
Rice Lake
CAMC/YPDT-Rice Lake-1
Centreton
Cobourg
720000
725000
730000
735000
740000
745000
750000

Figure 27.5. Location of the exploratory borehole and nested monitoring well CAMC/YPDT-Rice Lake-1 in the Rice Lake area. Both the geological and the geophysical properties of CAMC/YPDT-Rice Lake-1 were logged.

Sharpe et al. (2004) has shown that both the origin and the nature of sediment infill of buried valleys in this area are complex. Hence, this bedrock valley and its sediment infill are currently being investigated through numerous lines of evidence. The gravelly facies and facies associations, as indicated in both the cored sediment and the seismic survey, indicate the important role of tunnel channels and very high-energy glacial meltwater flows to help explain much, if not all, of the observed stratigraphic sequence (Russell et al. 2004a, 2004b). Other theories, such as preglacial and subaerial fluvial processes, may also help explain the nature of the buried valleys in the area. These different hypotheses are currently being considered and tested to help make informed predictions concerning aquifer potential and groundwater movement in these buried valleys.

The continuous data of the seismic profiles are helping to improve knowledge of the geometry of these buried valleys and the processes of formation. At present, it is not clear if the bedrock valley itself was sculpted by a subglacial meltwater event, or was of a preglacial fluvial origin, or was possibly a combination of both. The location of the valley system relative to a nearby re-entrant of the Niagara Escarpment at the Forks of the Credit, and relative to the Laurentian Channel are factors to be considered. One possibility is that a preglacial fluvial bedrock valley existed in this area, which became a flow path for subglacial meltwater discharges.

Figure 27.4 illustrates an interpretation of the bedrock topography relative to the Laurentian Channel. It is based on limited information from water wells that intersected bedrock and interpretation polylines that assume this valley system continues to the Laurentian Channel.

Rice Lake Borehole

A borehole drilling project was completed near the height of the ORM south of Rice Lake to investigate the hydrostratigraphy in this area (*see* Figure 27.5). Water-well records indicate that the area is underlain by a thick sediment package, yet very little is known about the stratigraphy of the eastern portions of the ORM.

The initial drilling was completed using the PQ coring system, which provided a continuous, high quality core of the sediment. Drilling was completed by All-Terrain Drilling of Waterloo, Ontario, in November 2003 and the core was logged in the field.

The depth to bedrock at this location is approximately 180 m and preliminary results indicate that the stratigraphy consists of fairly shallow ORM sandy sediments, underlain by Newmarket Till at a depth of about 20 m. The Newmarket Till is underlain by another sandy aquifer, which, in turn, is underlain by significant thicknesses of fine-grained glaciolacustrine and diamict units. The lower sand aquifer and fine-grained sediments are interpreted to be correlative with the "Lower Sediments" of the GSC's stratigraphic model (Sharpe et al. 1999), although the regional context of these sediments has not been evaluated. Of significance is a second till unit, nearly 30 m in thickness, found at a depth of about 110 m. No significant aquifers were found within the borehole, but the emerging hydrostratigraphic framework will aid in focussing efforts for aquifer delineation.

Downhole geophysics logging was completed shortly after the borehole construction. Due to the deep water table (approximately 30 m below ground surface), several of the tools (including neutron and P-wave velocity) were not as effective in the upper part of the borehole. Nonetheless, preliminary results indicate that the downhole geophysical profile corresponds well with the logged physical stratigraphy.

Detailed logging of this core may still be undertaken to provide a complete high-quality subsurface record in this area of poor data quality (e.g., Sharpe et al. 2003; Russell, Sharpe and Hunter 2004).

Following drilling, a monitoring well nest (consisting of 3 wells) was installed in the borehole to facilitate long-term monitoring of water levels and water quality. This monitoring well nest will become part of the Ontario Ministry of Environment's Provincial Groundwater Monitoring Network. The Lower Trent Conservation Authority, in co-operation with the Ministry of the Environment will undertake maintenance of these wells into the future.

Port Perry Seismic Survey

A seismic survey is also being considered just west of Port Perry to aid the Region of Durham secure a new groundwater supply for that community. Currently, groundwater from the existing Port Perry wells is of relatively poor quality from an aesthetic perspective (i.e., poor taste, and staining due to iron and manganese). To date, test spreads have been completed southwest of the town and the data are currently being assessed to determine the suitability of that area for a seismic survey. If it proceeds, the seismic survey is scheduled for the fall of 2004. Should a suitable target be identified, a borehole-drilling program will be initiated in co-operation with the Region of Durham.

2003 Field Trip

In order to better convey the results of ongoing work, a field trip was undertaken with planners and hydrogeologists from partner agencies. The GSC staff helped lead the field trip. A field guidebook was assembled and distributed to attendees. The goal of the trip was to provide an overall understanding of the regional geological setting and its role in controlling groundwater movement across the Oak Ridges Moraine area.

Ongoing Geological Interpretation

In ongoing numerical groundwater modelling studies (Wexler et al. 2003; Earthfx Incorporated 2004), there remains a significant need for high-quality data and an understanding of the geological processes controlling groundwater movement. Over the past year, much progress has been made in assembling digital geological layers across the Credit Valley, Lake Simcoe, Toronto Region and Central Lake Ontario conservation authority watershed areas (Kassenaar, Holysh and Gerber 2003). This work has been instrumental in assisting the numerical modelling process to constrain uncertainty. The digitally generated geological layers will be continually improved as new data becomes available, and will be used to test conceptual models and to incorporate these new concepts into the developing knowledge base.

FUTURE WORK

Field activities are planned for the remainder of 2004 and 2005 to complete the field projects already started and outlined above. As well, some new field projects are being planned. Key among these are

- Additional borehole drilling to bedrock using PQ coring technology at strategic locations as indicated by the seismic survey results. Targets would be selected to optimize understanding of the overall ORM groundwater flow system;
- Additional seismic surveys to aid communities in the search for additional groundwater supplies; and
- Additional seismic work in the Rice Lake area across a possible tunnel channel to aid in the interpretation of the stratigraphy in the east side of the moraine.

ACKNOWLEDGMENTS

Personnel from the GSC provided important technical assistance with these field projects. In particular, Sue Pullan, Hazen Russell and Dave Sharpe provided data processing and interpretation related to ORM characterization and buried-valley aquifer delineation. Jim Hunter, Ron Good and Rob Burns provided supplemental data.

Kim Gilder (CAMC) provided assistance with data collection and the preparation of this report.

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28. Project Unit 04-028. An Investigation into Buried Valley Aquifer Systems in the Lake Simcoe Area

S. Holysh[1], S.D. Davies[1] and D. Goodyear[2]

[1]Conservation Authorities Moraine Coalition
[2]Lake Simcoe Region Conservation Authority, Newmarket, Ontario

INTRODUCTION

The Sedimentary Geoscience Section (SGS) of the Ontario Geological Survey (OGS) is continuing a program of further refining the understanding of the subsurface geology in southern Ontario (Kelly, Sarvas and Baker 2003). The overall objective of this program is to provide municipalities and conservation authorities with a sound geological framework from which they can make effective land use decisions with respect to groundwater resources.

The Conservation Authorities Moraine Coalition (CAMC) is a partnership of the 9 conservation authorities having jurisdiction on the Oak Ridges Moraine. Together with the Regional Municipalities of York, Peel and Durham and the City of Toronto, this partnership has established a joint, long-term goal of understanding the groundwater system across a large part of southern-central Ontario. Through this partnership, a number of technical and policy studies have been undertaken. The studies can be loosely grouped into one of 4 broad categories: 1) data management; 2) data collection; 3) technical analyses; and 4) policy and planning.

In 2004, the OGS, under its Groundwater Resource Project (GRP) program, partnered with Lake Simcoe Region Conservation Authority and the CAMC to investigate buried-valley aquifer systems in parts of the Lake Simcoe area (Figure 28.1). The OGS, CAMC and Geological Survey of Canada (GSC) have a common interest in evaluating the significance of buried valleys as a potentially important aquifer type and are working in partnership regarding the investigation of buried valley aquifers between Lake Simcoe and the Niagara Escarpment. The locations of buried-valley aquifers are poorly known, however, they are hydrogeologically significant in the Great Lakes area and particularly in Ontario (e.g., Sharpe and Russell 2004). They are also difficult to delineate and characterize (e.g., Sharpe et al. 2004). Hence, the need for the acquisition of high-quality data to refine our understanding of these valleys.

This article discusses the preliminary work undertaken for the initial phases of this ongoing project.

BACKGROUND

Through projects carried out under the CAMC partnership, a revised bedrock topography map has been produced (Earthfx Incorporated 2004) for the area to the west and south of Lake Simcoe. This revised bedrock surface more clearly combines actual bedrock topography data points (drilled wells) with geological conceptualization, to delineate a Laurentian valley system running between Georgian Bay and Lake Ontario.

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As a result of this preliminary bedrock topography mapping, and some drilling that has taken place within the channel (Holysh and Davies 2003), it has been recognized that aquifer systems within these deeper bedrock valley systems are not well understood. There is considerable potential for communities that sit above these bedrock valley systems to develop deep, high-capacity wells to provide additional municipal water supplies. Two main benefits of tapping deeper aquifer systems are 1) in general, deeper aquifers are less connected to the surface environment and are, therefore, better protected from surface contamination; and 2) the aquifers are more regional in their extent and, therefore, are typically not directly linked to local surface water systems. Pumping from these deeper aquifers will likely not adversely influence sensitive local cold-water aquatic ecosystems.

The project has set out to better characterize these deeper bedrock valley systems, initially through targeted seismic reflection surveys, and subsequently by drilling targeted aquifers. Communities that are actively looking for additional groundwater resources (e.g., Schomberg, Barrie–Angus area, Bradford and Orangeville) are to be targeted for field work programs.

2004 FIELD PROGRAM

To date, field work has been completed in the Schomberg area, and is ongoing in the Barrie–Angus area (*see* Figure 28.1). Preliminary discussions have been held with the communities of Orangeville and Bradford to complete seismic work in those areas.

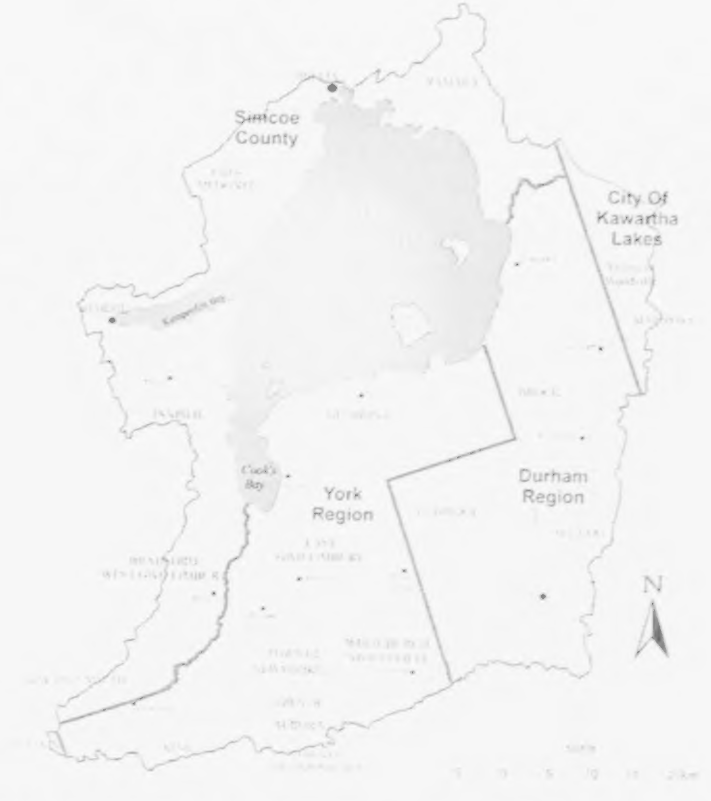

Figure 28.1. Location of study area. Schomberg is situated in the southwest corner of the map.

As a result of this preliminary bedrock topography mapping, and some drilling that has taken place within the channel (Holysh and Davies 2003), it has been recognized that aquifer systems within these deeper bedrock valley systems are not well understood. There is considerable potential for communities that sit above these bedrock valley systems to develop deep, high-capacity wells to provide additional municipal water supplies. Two main benefits of tapping deeper aquifer systems are 1) in general, deeper aquifers are less connected to the surface environment and are, therefore, better protected from surface contamination; and 2) the aquifers are more regional in their extent and, therefore, are typically not directly linked to local surface water systems. Pumping from these deeper aquifers will likely not adversely influence sensitive local cold-water aquatic ecosystems.

The project has set out to better characterize these deeper bedrock valley systems, initially through targeted seismic reflection surveys, and subsequently by drilling targeted aquifers. Communities that are actively looking for additional groundwater resources (e.g., Schomberg, Barrie–Angus area, Bradford and Orangeville) are to be targeted for field work programs.

2004 FIELD PROGRAM

To date, field work has been completed in the Schomberg area, and is ongoing in the Barrie–Angus area (*see* Figure 28.1). Preliminary discussions have been held with the communities of Orangeville and Bradford to complete seismic work in those areas.

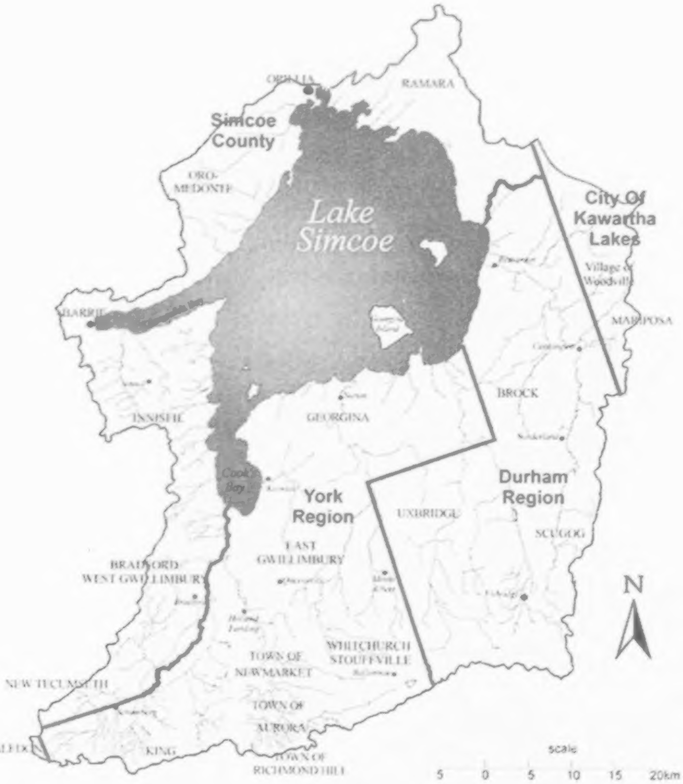
ORILLIA
RAMARA
Simcoe County
ORO-MEDONTE
Lake Simcoe
City Of Kawartha Lakes
Village of Woodville
BARRIE
MARIPOSA
BROCK
INNISFIL
GEORGINA
Cook's Bay
York Region
Durham Region
UXBRIDGE
SCUGOG
EAST GWILLIMBURY
BRADFORD WEST GWILLIMBURY
N
WHITCHURCH STOUFFVILLE
TOWN OF NEWMARKET
NEW TECUMSETH
TOWN OF AURORA
CALEDON
KING
TOWN OF RICHMOND HILL
scale
5
0
5
10
15
20km

Figure 28.1. Location of study area. Schomberg is situated in the southwest corner of the map.

Schomberg Seismic Summary

The Schomberg seismic profile consists of an approximately 9 km east-trending transect along 18th Sideroad, across the extension of the Holland Marsh lowland, south of Highway 9. In the east, the line begins adjacent to Highway 400 and extends westward along 18th Sideroad, ending west of Highway 27. The line passes about 3 km south of the community of Schomberg (Figure 28.2).

The transect was positioned to provide a seismic profile of interpreted buried valleys, both in bedrock (Laurentian valley) and in overlying sediment (base of Holland Marsh valley). Subsurface reflector patterns are of good quality and provide important information to help re-construct the three-dimensional geology of the area. The general picture that is evident from an initial assessment of these data reveals a prominent, deep, across-profile basal reflector beneath a complex overlying stratigraphy. Within the overlying sediment, a 150 m deep valley structure, 3 to 4 km wide, is evident.

Figure 28.3 shows the seismic profile in the vicinity of Highway 27. It should be noted that the processing of the seismic data, as depicted in Figure 28.3, is preliminary at this stage.

The strongest reflectors (high amplitude) are observed to dip gently to the west and they occur at the base of the profile. These reflectors are interpreted to represent the surface of limestone bedrock and to indicate the apparent erosion of shales from the Georgian Bay and Whitby formations along the western part of the survey line. The Laurentian valley bottom, which is represented by this basal reflector, has a broadly undulating structure along this line and becomes deeper (>200 m below surface) to the west. The line did not extend far enough west to detect the western slope of the broad Laurentian valley, which is interpreted to be nearer to the Niagara Escarpment some 18 km to the west. It is unclear whether the seismic line crossed the deepest part of the Laurentian valley.

The Schomberg seismic profile also indicates the presence of a buried valley (not shown in Figure 28.3) eroded into overburden and overlying the Laurentian bedrock valley. This overburden valley is inferred to be part of a previously interpreted subglacial channel that extends from Cook's Bay in Lake Simcoe (Todd et al. 2003) to south of Nobleton (Pugin, Pullan and Sharpe 1999). The reflector pattern

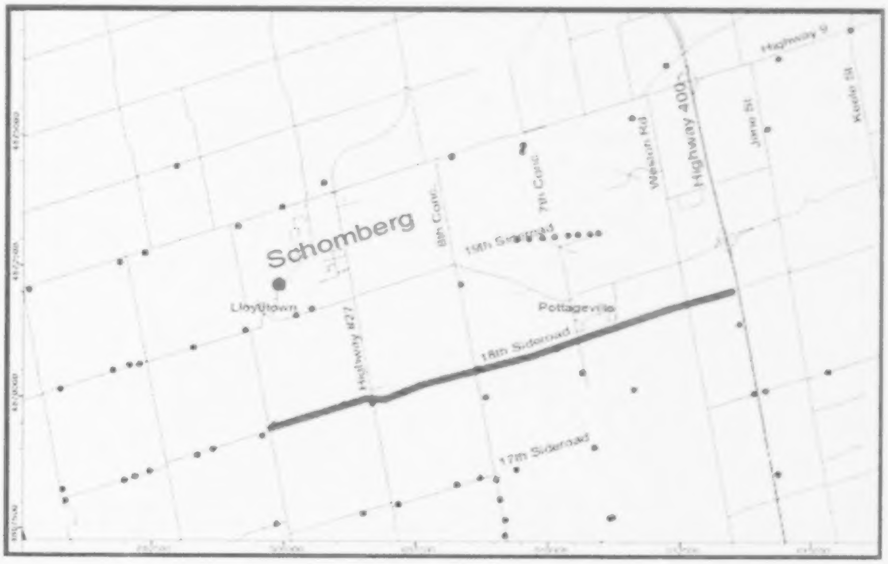

Figure 28.2. Location of Schomberg seismic line showing key geological data sources in the area (small dots) as well as the recently completed Schomberg cored borehole (large dot between Lloydtown and Schomberg).

within the channel is poorly defined and generally low amplitude and is inferred to indicate sandy to silty sand channel-fill sediments (Pugin, Pullan and Sharpe 1999; Russell, Arnott and Sharpe 2003). Some higher strength, hummocky reflectors likely indicate more gravelly sediment along the lower 10 to 25 m of the channel structure. The east wall of the buried channel is steep and in alignment (and likely of similar slope) with the east walls of both the Holland Marsh and a Nobleton seismic profile approximately 6 km to the south (Pugin, Pullan and Sharpe 1999). This inferred steep channel wall truncates subparallel reflectors, which indicate horizontally bedded sediments in the uplands adjacent to the channel.

As seen on the right side of Figure 28.4, a strong reflector about 20 m below ground surface may be the base of the Newmarket Till. This inference is in keeping with surface mapping in nearby uplands (Sharpe et al. 1997) and with OGS-PJB-82, a borehole located 1 concession south of the east end of the seismic line (Sado et al. 1983). These investigations showed a 17 m thickness of Newmarket Till, with the top of the till approximately 10 m below surface. Below the high-amplitude reflector, subparallel reflector patterns are interpreted as over 100 m of lower sediment. This likely includes older formations such as the Scarborough Formation (Sado et al. 1983).

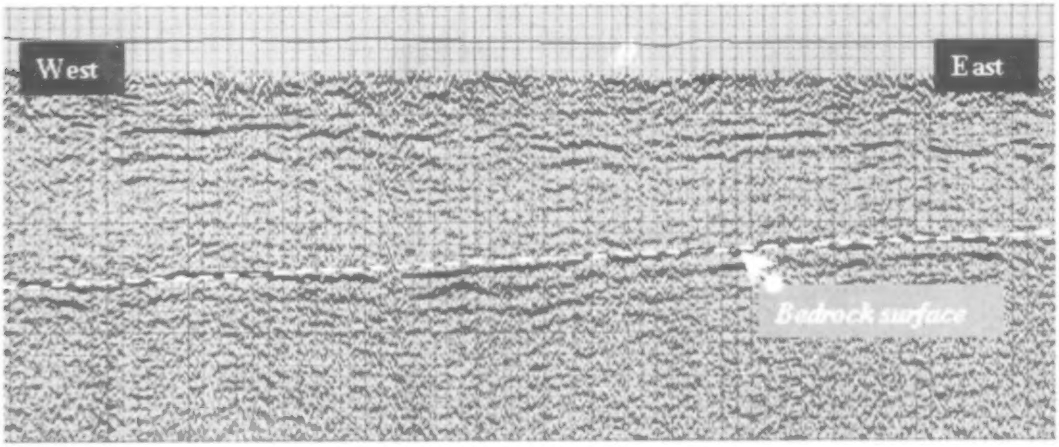

Figure 28.3. West portion of Schomberg seismic profile in the vicinity of Highway 27. Note the inferred bedrock surface dipping to the west.

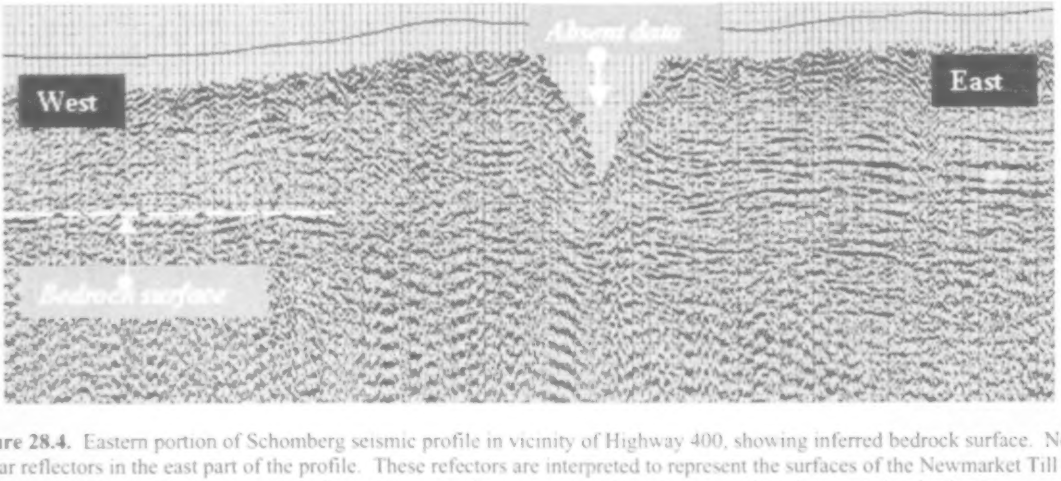

Figure 28.4. Eastern portion of Schomberg seismic profile in vicinity of Highway 400, showing inferred bedrock surface. Note planar reflectors in the east part of the profile. These refectors are interpreted to represent the surfaces of the Newmarket Till and the lower sediments. The absence of similar reflectors in the west part of the seismic profile is interpreted to be due to truncation by a sediment channel just to the left of the area of absent data. The absent data are due to inaccessibility.

The seismic reflector pattern indicates that the west margin of the sediment channel rises moderately from the channel base to an upland further west. The channel margin reflector truncates underlying reflectors that are roughly tabular and of moderate to high strength. This seismic character suggests a coarser sediment package beneath the west upland as compared with the eastern upland. The first strong reflector occurs between 40 and 50 m below surface on this western margin. Based on seismic facies and its undulating upper surface (drumlins?), this reflector is interpreted as the top of the Newmarket Till. This interpretation is in accord with inferred Newmarket Till from cored sediment and borehole geophysics obtained at a recently drilled deep borehole in Schomberg (*see* Figure 28.2 for location).

The seismic profile beneath the (inferred) Newmarket Till is characterized by high strength, undulating reflectors. Based on the core and borehole geophysical data from the Schomberg borehole, this pattern corresponds with 2 overall fining-upward sequences consisting of gravel, sand and silt–clay rhythmites. Limestone of the Lindsay Formation was confirmed at 153 m below ground surface (~100 m asl) at the Schomberg borehole.

Barrie–Angus Area Seismic Summary

A seismic survey was initiated in the area west of Barrie and east of Angus to investigate the nature of sediment infill and the bedrock topography in this area. The area is of interest scientifically and from a municipal water supply perspective due to the presence of both an interpreted tunnel channel, extending to Kempenfelt Bay, and the Laurentian Channel in the Angus area. Both of these features may contain significant aquifers.

The project was initiated in the late summer 2004 and is currently underway. Seismic data are being collected by Geophysical Applications Processing (GAPS) of Guelph. The GSC will be aiding in the interpretation of this seismic data. An initial postulation, based on previous work, is that sediment grain sizes would fine to the southwest in moving further from Kempenfelt Bay (*see* Figure 28.1). Eight test spreads were, therefore, completed east and northwest of Angus in order to choose the location of the most suitable seismic survey line. Four of these test spreads were completed between Barrie and Angus and favourable reflector patterns (aquifer targets) were identified to help position the collection of seismic profiles for aquifer delineation.

FUTURE WORK

The ongoing seismic work will continue through 2004 and into 2005 with completion of the seismic lines and possibly with follow up drilling. The results will be communicated in a timely fashion to affected municipalities and conservation authorities so that they may incorporate the results into their work plans.

ACKNOWLEDGMENTS

Susan Pullan and David Sharpe of the GSC helped with the preliminary interpretation and assessment of the Schomberg seismic line. Kim Gilder (CAMC) assisted with the preparation of this report.

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29. Project Unit 04-030. Sinkhole Investigation in the Ausable Bayfield Conservation Authority Watershed and Surrounding Area

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[1]Waterloo Hydrogeologic Inc., Waterloo, Ontario

INTRODUCTION

The Ausable Bayfield Conservation Authority (ABCA) was provided funding by the OGS (under its Groundwater Resource Project (GRP) program) to have Waterloo Hydrologic Inc. undertake a study of local sinkholes. The current study is a continuation (or "Phase 2") of a previous study (*see* "Background"). The present work was initiated to improve the understanding of local surface water–groundwater conditions around sinkholes, with an emphasis on sinkholes identified in the former townships of Hibbert and Tuckersmith. Within the study area, more than 50 sinkholes have been identified, most of which occur in areas where bedrock is overlain by a thin cover of overburden. The sinkholes are surface expressions of karst formed within the underlying sequence of Devonian carbonate bedrock formations. Groundwater flows rapidly through karstic aquifers and can quickly transport contaminants to water wells within karstic bedrock with little attenuation. It is important to identify the overall extent of karst features to support groundwater management initiatives within the watershed.

In order to provide a better understanding of the lateral and vertical extent of karst, the area for the current sinkhole study was expanded beyond that of the previous study to include portions of the Upper Thames Conservation Authority, Maitland Valley Conservation Authority and Ausable Bayfield Conservation Authority (Figure 29.1).

BACKGROUND

In 2003 and 2004, Waterloo Hydrogeologic, Inc. completed the Ausable Bayfield Conservation Authority Sinkhole Investigation Study in conjunction with ABCA, the Municipalities of West Perth and Huron East, and the Ministry of the Environment (MOE) (Waterloo Hydrogeologic Inc. 2004). The investigation involved a compilation and evaluation of regional and local groundwater resources information in the Municipalities of Huron East and West Perth. The study area is primarily agricultural, with intensive cash-crop farming and livestock operations. Surface runoff has been observed draining into sinkholes, which are thought to provide a direct link to underlying aquifers, and potential pathways for contamination.

As interpreted from water well records, groundwater surfaces are depressed by as much as 100 m in the karstic areas of the Ausable Bayfield watershed. Regional groundwater surface mapping and subsurface geologic information from water well records indicate that karstic bedrock extends over a

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Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.29-1 to 29-6.

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much larger area than the karst surface expression suggests. The depression in the groundwater surface correlates well with the mapped subcrop extent of the Middle Devonian Lucas Formation of the Detroit River Group in the region.

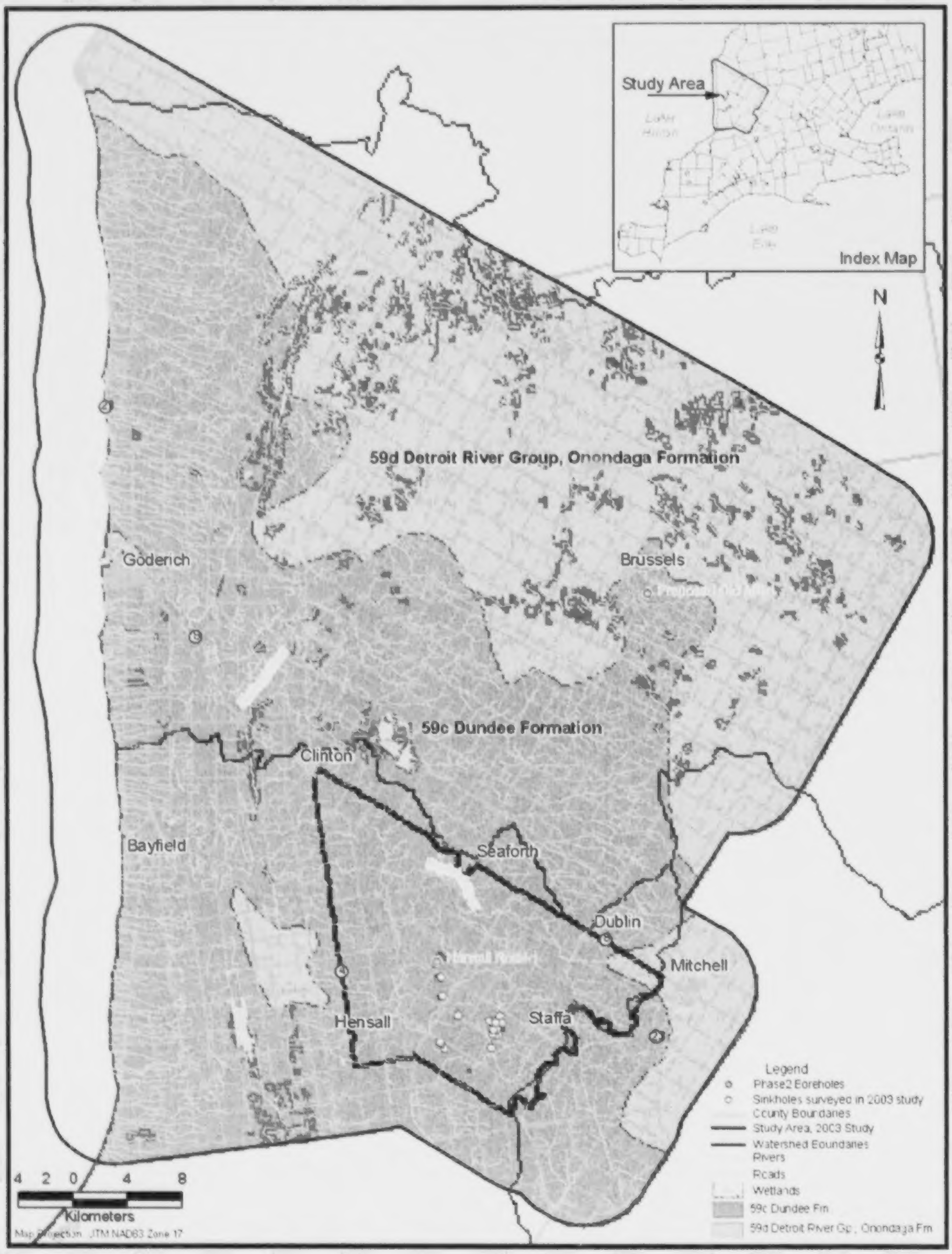
Study Area
Lake Huron
Lake Ontario
Lake Erie
Index Map
N
59d Detroit River Group, Onondaga Formation
Goderich
Brussels
59c Dundee Formation
Clinton
Bayfield
Seaforth
Dublin
Mitchell
Hensall
Staffa
Legend
Phase2 Boreholes
Sinkholes surveyed in 2003 study
County Boundaries
Study Area, 2003 Study
Watershed Boundaries
Rivers
Roads
Wetlands
59c Dundee Fm
59d Detroit River Gp., Onondaga Fm
4 2 0 4 8
Kilometers
Map Projection: UTM NAD83 Zone 17

Figure 29.1. Location of study area.

OBJECTIVES

The goal of the present ABCA sinkhole study is to undertake a regional subsurface investigation of karst as a basis for local source water protection planning and to develop three-dimensional geological and hydrogeological models. To date, the sparse subsurface data available in the region has limited the conceptual model in terms of describing the stratigraphic controls and three-dimensional character of the karst formation.

A drilling program designed to provide the subsurface information needed to extend the understanding of the occurrence and stratigraphic controls on karst formation within the area was undertaken during the summer of 2004. Additional field work, to be completed in the fall of 2004, includes the drilling of a second borehole, followed by downhole geophysics and tracer studies to support the development of the geological and hydrogeological mapping.

DRILLING PROGRAM

The overburden portion of the Hensall Road-1 borehole (MOE well number A008161) was drilled and logged by W.D. Hopper and Sons, Limited, on July 19 to 20 using a DrillTech T-40-K rotary rig. Stainless steel casing was keyed into the weathered bedrock surface and set at a depth of 17.68 m below ground surface using portland grout. The contact between the overburden and the weathered limestone bedrock was determined to be at 15.85 m below ground surface. The well was tested and observed to produce less than 1.0 gallon per minute (5.45 m^3/day).

Rock-core drilling for Hensall Road-1 began on August 3, 2004 using a CME 750 rotary drill rig outfitted for PQ coring using a wireline system. Drilling was performed by All-Terrain Drilling Limited. The work spanned a total of 7 days and the borehole was completed on August 11, 2004, at a total depth of 103.79 m below ground surface. Continuous rock core was collected in 1.5 m flights from 17.68 to 103 m below ground surface. A high-resolution digital photograph of each 1.5 m core run was taken immediately after recovery of the rock core to provide a visual record of each depth interval. In addition, each core run was logged in detail on site.

Each core run took, on average, 9 minutes to drill, and a total of 14 minutes in total to drill, retrieve the core, and break down the core barrel. Loss of drill bit circulation water and occasional equipment downtime reduced drilling progress. Water circulation was lost the first day at a depth of 19.20 m and did not return for the remainder of the drilling. Thus, a large amount of water was used to continuously core the rock at this location.

DRILLING RESULTS

Core recovery was better than 95%. Losses occurred on a few occasions, usually when significant (>10 cm thick) poorly lithified gravel or clay-rich zones were observed in the core or when problems were encountered with drilling (e.g., the core barrel did not properly lock into the drill rods).

Figure 29.2 shows photographs from a number of sections of the core, including vuggy and rubbly zones. A simplified log of the interpreted geological contacts encountered in the borehole is provided in Figure 29.3.

Water was intersected in the borehole at a depth of 97.54 m. This depth is comparable to depths recorded on MOE well records in the area which indicate the water table to be at a depth of around 100 m.

Based on regional bedrock mapping (Johnson et al. 1992) and work completed by Waterloo Hydrogeologic (Waterloo Hydrogeologic Inc. 2004), the bedrock drilling is thought to have intersected the Dundee Formation and Lucas and Amherstburg formations. The Dundee Formation is a fossiliferous medium-brown limestone with chert nodules, while the underlying Lucas Formation of the Detroit River Group consists of limestones and dolostones alternating with anhydritic dolostones, and thin beds and inclusions of anhydrite and halite (Johnson et al. 1992).

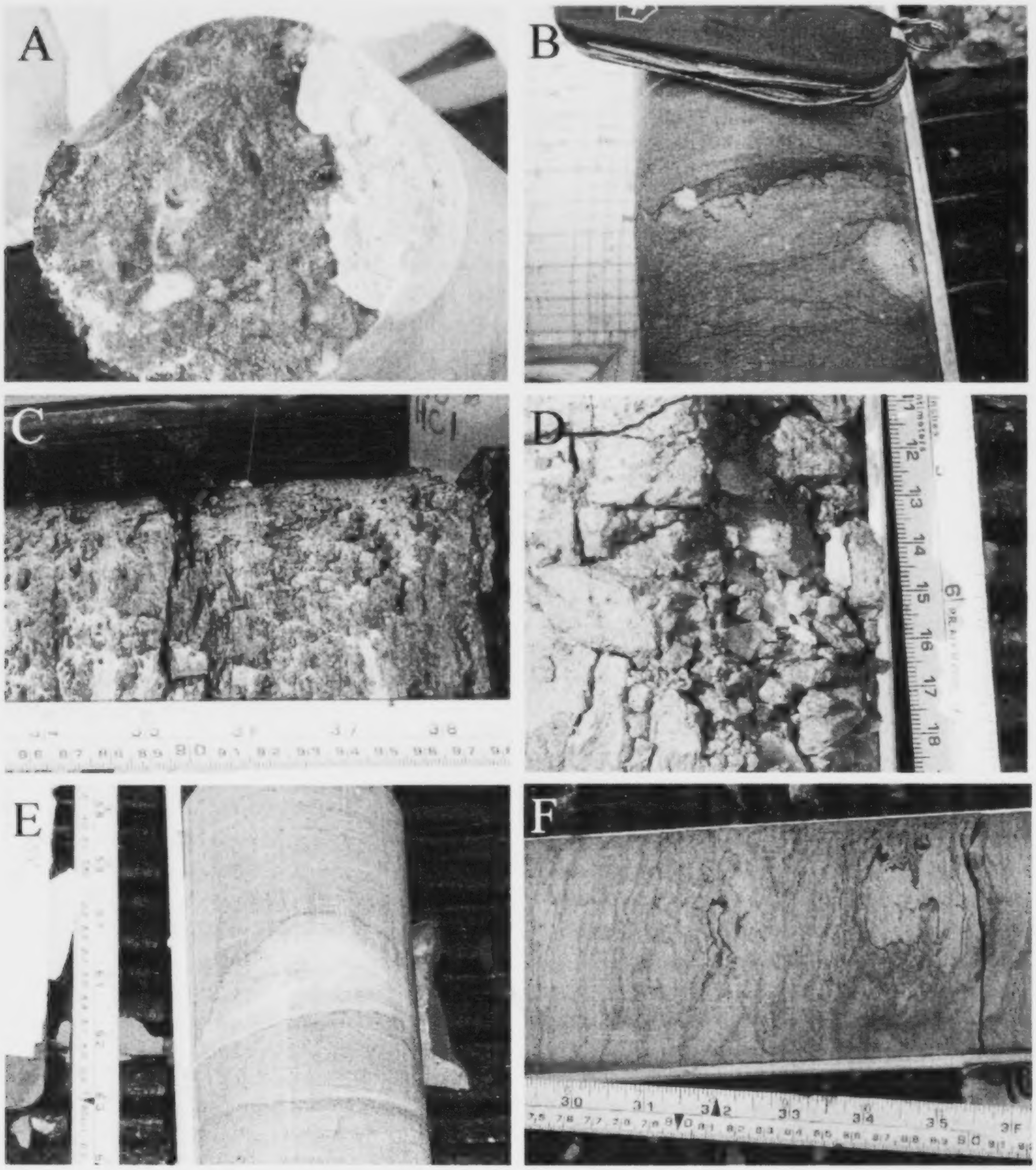

Figure 29.2. Example of features observed in core from the Hensall Road-1 borehole. A) Crystalline calcite infillings on fracture surfaces and fossils; B) brown cemented lime mud beds that terminate at stylolites; C) vuggy limestone beds; D) blue celestite infilling in some fractures; E) erosional surfaces; F) highly distorted black banding.

The drill core showed that the Dundee Formation contained frequent large (up to 3 cm thick) stylolites. At a depth of 29.8 m, a 3 cm thick curved bed of white limestone was present, below which the rock changed from fossiliferous limestone to banded grey-brown limestone with no visible fossils. Furthermore, by 31.86 m, light pink-beige dolostone was encountered. Based upon these observations, a preliminary interpretation suggests that the contact between the Dundee and Lucas formations in the Hensall Road-1 borehole is located at a depth of 29.8 m (*see* Figure 29.3).

The Lucas Formation contained frequent unlithified (rubbly appearing) and clay-rich beds as well as zones containing frequent and large (up to 5 cm in length) vugs. Therefore, it is interpreted that the karst is developing within this formation.

The contact between the Lucas and Amherstburg formations was more difficult to discern. The Amherstburg Formation is described as bituminous dolostone with oolitic bioclastic and coralgal zones (Johnson et al. 1992). Ooids were only observed near the very bottom of the core at a depth of 103.55 m. However, at 81.85 m, the nature of the bedrock appears to change. Above this depth, the bedrock consisted of alternating limestone and dolostone beds with needle-like disconnected vugs interpreted to be caused by dissolution of evaporite minerals. Below this, the bedrock becomes more competent and uniform in appearance, with a lack of needle-like vugs, and the beginning of continuous, strong black bituminous banding. No limestone is observed below a depth of 81.85 m. The observed thickness of the Lucas Formation (50 m) in the core is consistent with published observations (Johnson et al. 1992). Thus, a preliminary assessment suggests the contact between the Amherstburg Formation and Lucas Formation may lie at a depth of approximately 81.85 m (*see* Figure 29.3).

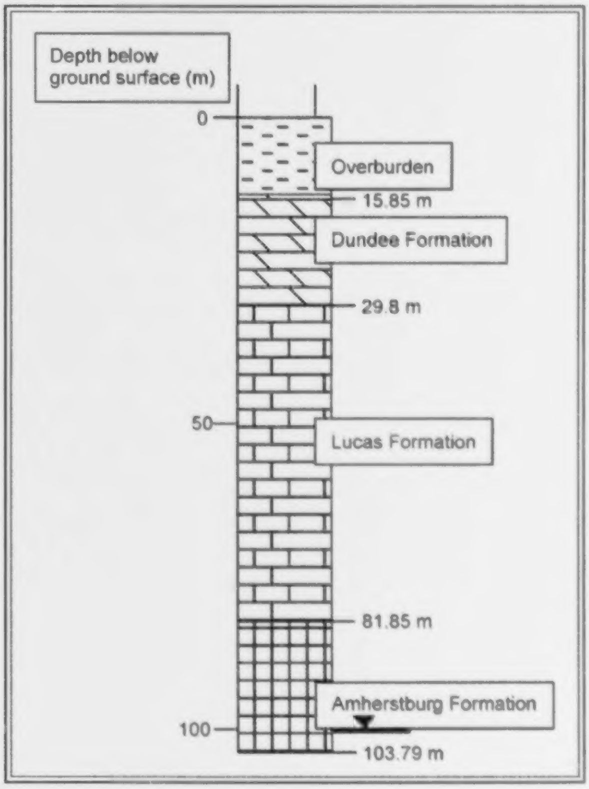

Figure 29.3. Simplified log of Hensall Road-1 borehole, showing the inferred contacts between Dundee, Lucas and Amherstburg formations.

The entire core exhibited frequent horizontal fractures and/or breaks and occasional steeply dipping (60 to 80° from horizontal) fractures. Iron precipitation, visible as orange staining, was occasionally observed on fracture surfaces to a depth of 78.73 m. A dark staining, interpreted to be manganese oxide, was observed frequently on fracture surfaces, visible as black dendritic precipitation, to a depth of at least 82.06 m.

FUTURE WORK

Re-logging of the core to identify additional features related to depositional environment and hydrogeological properties is scheduled for September 2004. Preparation for drilling of a second borehole is underway.

Borehole geophysical logging will be performed to help correlate formations or units between boreholes and water wells. Correlation from well to well enables the mapping of formation thickness and geological contact elevations, and may provide indirect insight into the physical properties that control karst formation in different carbonate lithologies (e.g., variation in density attributable to degree of cementation).

A groundwater tracer study may be undertaken at 2 sinkhole locations (the "Chiselhurst" and "Tuckersmith" sinkhole "fields" (*see* Figure 29.1 for general locations between Hensall and Staffa)). These 2 sinkholes drain the largest and second largest areas out of all the mapped sinkholes in the region. Tracer tests will improve our understanding of the connectivity between the sinkholes and the shallow (20 to 40 m deep) and deep (100 m deep) aquifers. During each tracer test, the monitoring well and nearby private wells will be sampled at regular intervals to record the arrival of the tracer and estimate travel times.

A local-scale groundwater model will be developed and calibrated by incorporating the new borehole, geophysical and sinkhole water level monitoring information. This model will be used to estimate groundwater velocities and the volume of water moving through the sinkholes into the underlying bedrock, and to assist in developing a three-dimensional conceptualization of the karst formation. Understanding the rate of percolation through the sinkhole and the response of the sinkhole capture area following a storm event will improve the understanding of the interaction between surface water and groundwater through sinkholes in the study area. The model will incorporate regional characteristics, such as the hydraulic conductivity and thickness of different geologic units, and will be developed using a discrete feature approach to physically represent the flow within the karst formation and the connection between the shallow and deep bedrock systems. Discrete elements will be utilized to represent overland flow, tile drainage, and flow through solution-enhanced fractures within the karst.

Further refinement of the model will be performed following the completion of the tracer study. The model will be updated to reflect new information related to groundwater velocities, flow rates and geological connections.

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30. Project Unit 04-031. North Lambton Groundwater Investigation

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INTRODUCTION

Under the Ontario Geological Survey's Groundwater Resource Project (GRP) program, the Ausable Bayfield Conservation Authority was provided funding to undertake a groundwater study in the northern part of Lambton County. The objective of the study is to better define the relationship between shallow overburden aquifers, bedrock aquifers and the waters of Lake Huron.

BACKGROUND

In the northern part of Lambton County, high-yield, shallow overburden and bedrock aquifers have been historically exploited for domestic and agricultural usage. In the past 15 years, reliance on groundwater has decreased due to the expansion of municipal water supplies from Lake Huron. However, recent concerns regarding lower lake levels has increased attention on using groundwater supplies for irrigation. Recently, a high-capacity bedrock water well has been constructed in the region and put into production for agricultural irrigation.

Previous studies conducted for local municipalities have identified the locations of overburden and bedrock aquifers in Lambton County. In general, however, the area lacks detailed stratigraphic and hydrogeological information necessary to evaluate potential hydraulic connections between the groundwater systems and surface water bodies.

STUDY SETTING

The study area is characterized by low topographic relief and is located on the southeastern coast of Lake Huron in an area commonly referred to as the Thedford Embayment (Figure 30.1). The study area is bounded by Lake Huron to the west, and to the east and south by the former shorelines of glacial lakes Algonquin and Nipissing. The study area includes the town of Grand Bend, the village of Port Franks, and Pinery Provincial Park.

Topography and Drainage

The study area is drained primarily by the Ausable River and its tributaries. The headwaters of the Ausable River begin in the Hibbert ward of West Perth, near the town of Mitchell. The original path of the river flowed in a southerly direction and swung west towards Arkona, where it encountered a bedrock high that forced the river northward to Grand Bend. At Grand Bend, the baymouth bar deposits of glacial

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Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.30-1 to 30-4.

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lakes Algonquin and Nipissing diverted the river sharply to the south (hence the name "Grand Bend"). The river then flowed parallel to the shoreline and eventually emptied into Lake Huron near the village of Port Franks. Two major diversions of the Ausable River occurred during the late 1800s. These diversions effectively drained a large area of marshland and small lakes. Prior to the diversions, the marshes and small lakes were likely sustained through periodic flooding of the Ausable River. The diversions altered the course of the Ausable River to its current flow path where it outlets at Port Franks and Grand Bend (Richardson 1949). A further consequence of these diversions was the abandonment of the Ausable River channel where it flowed parallel to the shoreline through Pinery Provincial Park.

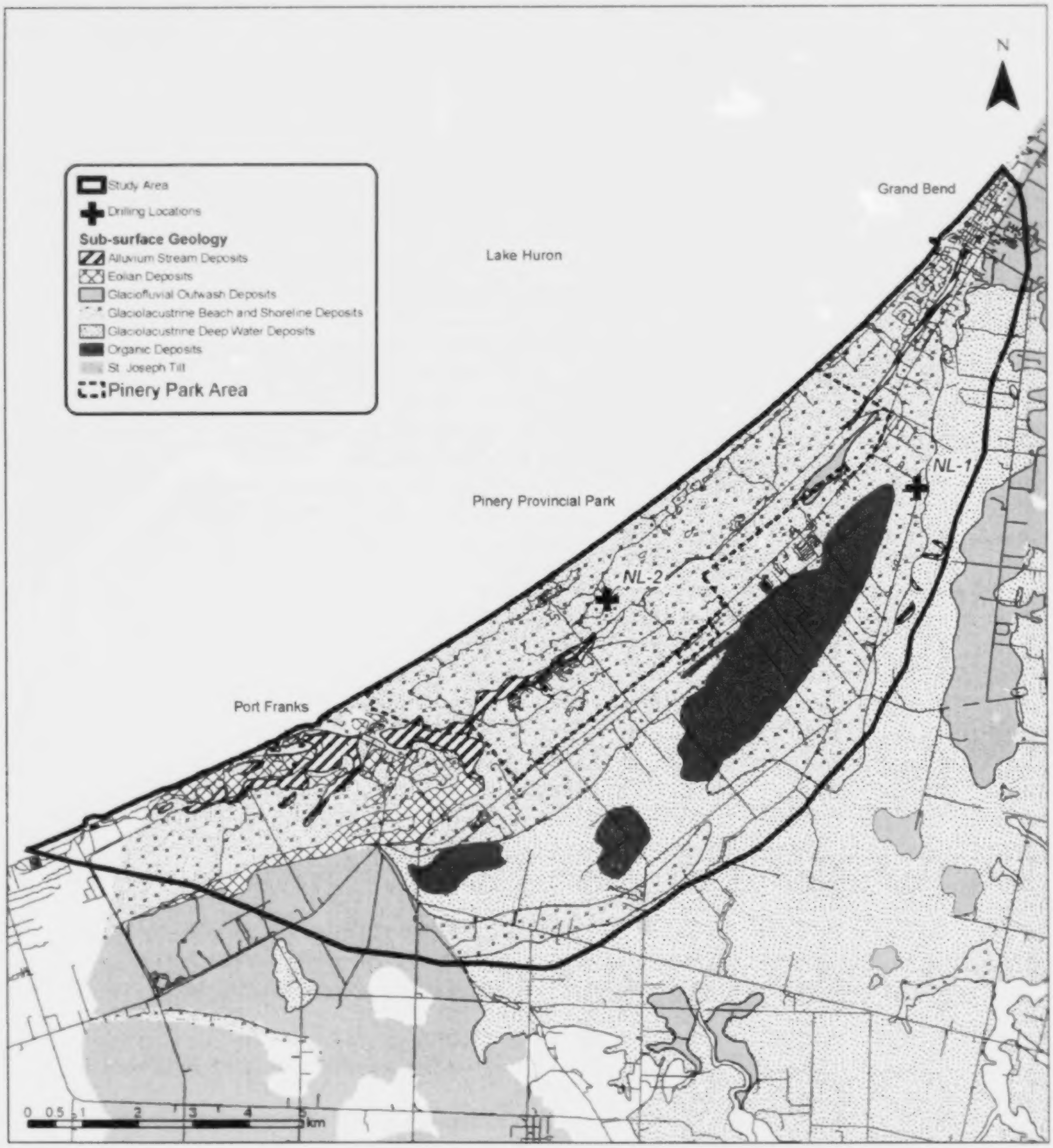
N
Study Area
Drilling Locations
Sub-surface Geology
Alluvium Stream Deposits
Eolian Deposits
Glaciofluvial Outwash Deposits
Glaciolacustrine Beach and Shoreline Deposits
Glaciolacustrine Deep Water Deposits
Organic Deposits
St. Joseph Till
Pinery Park Area
Grand Bend
Lake Huron
NL-1
Pinery Provincial Park
NL-2
Port Franks
0 0.5 1 2 3 4 5 km

Figure 30.1. Location of study area.

Geology and Hydrogeology

The study area is underlain by carbonate bedrock of the Middle Devonian. Two formations are present: the Dundee Formation and the underlying Lucas Formation of the Detroit River Group (Hewitt 1972).

A regionally significant bedrock aquifer is located within the upper portions of the Dundee Formation within the study area. This aquifer is highly productive and is used extensively outside the study area for domestic water supplies.

The St. Joseph Till, directly overlying the Paleozoic bedrock, is associated with the most recent glacial advance in the area (the Port Huron Stade, ca. 13 000 years ago) during the Quaternary Period. After the Port Huron Stade, sediments associated with glacial lakes Algonquin and Nipissing, including lacustrine clays and beach and baymouth sands and gravels were deposited over much of the study area (Cooper 1979). Locally, the Ausable River system and Lake Huron have reworked the Quaternary deposits of the study area.

The shallow overburden aquifer is situated primarily within the Algonquin and Nipissing baymouth bar deposits and recent eolian dunes distributed along the shoreline of Lake Huron. This high-yield aquifer was extensively used as a source of domestic drinking water, typically through shallow (less than 10 m deep) sandpoints or bored wells. Reliance on this shallow overburden aquifer has decreased with the expansion of the Lake Huron municipal water supplies. One study performed in the Town of Bosanquet indicated a repeated occurrence of bacterial contamination in the groundwater of this shallow overburden aquifer (B.M. Ross and Associates Limited 2001).

2004 FIELD PROGRAM

Methodology

The field program for the North Lambton groundwater study was developed following a literature review and compilation of available data. The literature review revealed that a network of piezometers within Pinery Provincial Park, screened within the overburden aquifer, were still in use for research activities by the University of Western Ontario. Permission was granted to the Ausable Bayfield Conservation Authority to incorporate borehole logs and measure water level elevations from this network.

Compilation of geological and hydrogeological data (including the logs of water wells and oil and gas wells) revealed little bedrock drilling in the study area. Bedrock drilling that had occurred was restricted to the peripheries of the study area. The majority of wells within the study area are shallow overburden water wells situated within the village of Port Franks and the town of Grand Bend.

Following the compilation of data, 2 drilling locations were selected to define stratigraphy within areas identified as having data gaps (Figure 30.1). In addition, a piezometer was installed in borehole NL-2, which penetrated to the bedrock aquifer, to provide a comparison of water levels between overburden aquifers, bedrock aquifers and Lake Huron.

Field Data Acquisition

Boreholes NL-1 and NL-2 were drilled using a mud rotary system. Samples of soil and rock cuttings were collected and logged at approximately 1.2 m intervals, with samples collected more frequently within variable stratigraphy.

NL-1 was drilled to a depth of 43.3 m, intersecting 7.3 m of brown, medium-grained sand, underlain by 34.7 m of grey, clayey silt with subordinate gravel, and 1.3 m of greyish brown, microcrystalline limestone. Dark, rounded wood chips were intersected near the bottom of the sand unit, between 5 m and 6 m depth. Two good quality water-bearing horizons were intersected at 1.4 m and 43 m.

NL-2 intersected 21.3 m of brown, medium-grained sand, underlain by 38.2 m of grey, clayey silt with rare gravel clasts, and 6.3 m of greyish brown, microcrystalline limestone. A high-yield, high-quality water-bearing horizon was intersected at a depth of 4 m, and a second, sulphurous water-bearing horizon at a depth of 60 m.

In addition to geological information obtained during drilling, UTM co-ordinates for pre-existing piezometers, drill sites, and water wells were collected for use in generating cross-sections. Water levels from all piezometers located in Pinery Park were measured on August 23, 2004.

FUTURE WORK

Geological field data, including borehole logs and existing maps, will be further analyzed in order to develop a stratigraphic model of the area. Water levels from the overburden and bedrock aquifers will continue to be monitored. Using all data sources, a local conceptual hydrogeological model will be developed to illustrate the relationship between overburden and bedrock aquifers and Lake Huron in the study area.

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31. Project Unit 04-029. Three-Dimensional Groundwater Flow Modelling in the Watersheds of Southwestern Ontario

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[2]Upper Thames River Conservation Authority, London, Ontario

INTRODUCTION

Under the Groundwater Resource Project (GRP) program, the Ontario Geological Survey (OGS) is funding a groundwater flow modelling project that is being undertaken by the Ausable Bayfield, Upper Thames River, Lower Thames Valley, Maitland Valley, Essex Region and St. Clair Region conservation authorities. The project involves the development of three-dimensional conceptual geologic and hydrogeologic models and the development, calibration, and application of a FEFLOW™ [3] groundwater flow model for the watersheds covering most of southwestern Ontario.

The study area is located in the extreme part of southwestern Ontario (Figure 31.1). Over 1.2 million people reside within the 20 000 km^2 study area, which is bound to the west by lakes Huron and St. Clair, and to the south by Lake Erie. The study area includes several watersheds managed by the 6 conservation authorities (herein referred to as the "6 CAs"). The numerous rivers and streams within these watersheds drain into Lake Huron, Lake St. Clair or Lake Erie.

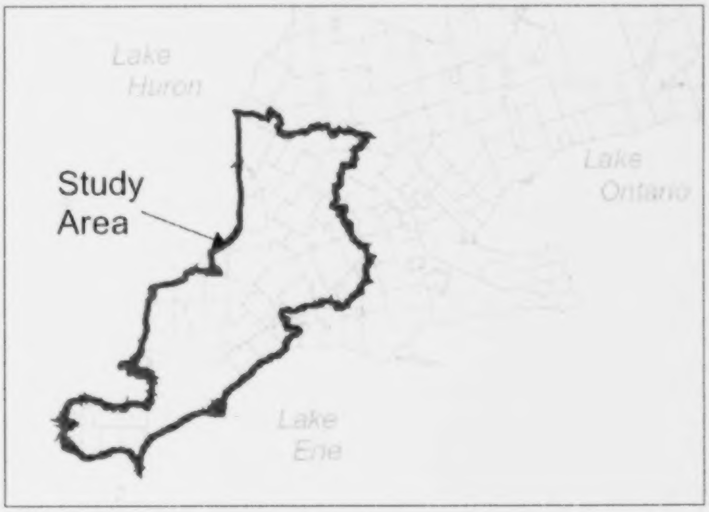

Figure 31.1. Study area for the 6 conservation authorities.

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[3] FEFLOW Interactive Graphics-based Finite Element Simulation System for Subsurface Flow and Transport Processes, v.5.106, June 2004. Copyright 1979–2004 by WASY Institute for Water Resources Planning and Systems Research Limited.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.31-1 to 31-4.

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BACKGROUND

The study area is characterized by intensive agricultural operations and industry that is concentrated primarily in urban areas (e.g., Sarnia, Windsor, London and Stratford).

Recently, the Ministry of the Environment (MOE) funded a series of regional groundwater studies across Ontario. These groundwater studies were completed between 2000 and 2003, and several of these studies were completed in various areas within each of the 6 CAs' jurisdictions. Key accomplishments of these studies were the characterization of the geological and hydrogeological settings and the development of regional mapping products. During completion of many of the regional studies, it was apparent that groundwater flow does not always follow surface watersheds. This is particularly true in karstic and deep, confined bedrock aquifers, such as are found in the Dundee and Lucas formations that underlie the study area.

OBJECTIVES

The purpose of the current study is to improve the current understanding of the groundwater flow system, including the linkages between deep regional bedrock aquifers and the shallow groundwater system. Based on the work conducted during the regional groundwater studies funded by MOE, it is understood that groundwater in the deep groundwater system flows through multiple watersheds and conservation authority jurisdictions, necessitating the regional approach adopted for this study. Understanding these processes is required to assess impacts to the groundwater or surface water regimes that may occur either locally or regionally.

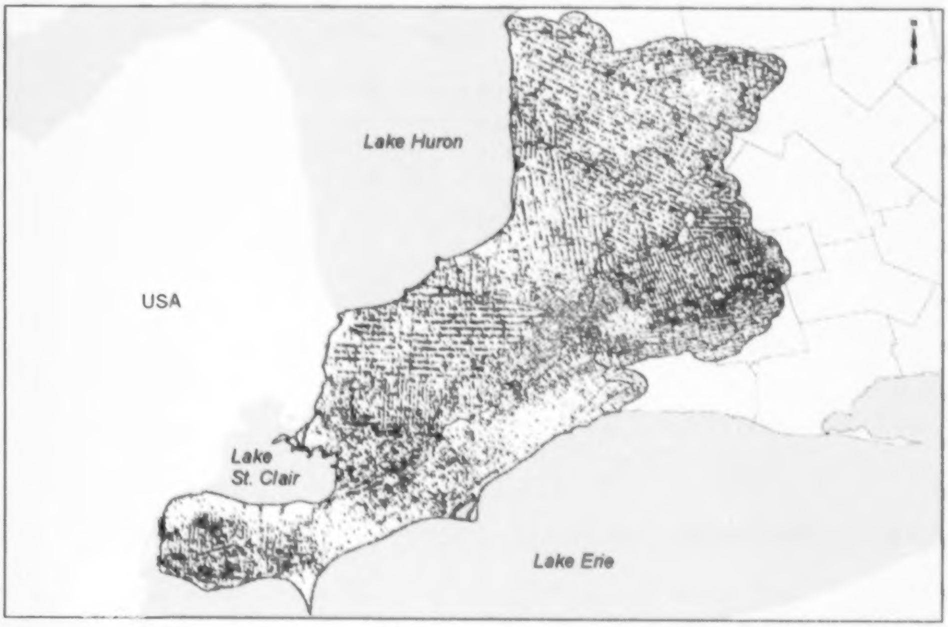

Figure 31.2. Locations of bedrock and overburden water wells in study area (*from* the Ontario Ministry of the Environment Water Well Information System database).

The focus of this report is the development of the conceptual model for the three-dimensional geologic and hydrogeologic models. The development, calibration, and application of a FEFLOW™ groundwater flow model for the entire study area will be completed during the remainder of 2004 and early 2005. Downhole geophysical logging of selected monitoring wells across the study area is also planned to take place during the fall of 2004 (Nicks, Flynn and Harrington, this volume) to refine the geologic conceptualization prior to the development of the FEFLOW™ model.

DATA COMPILATION AND GEOLOGIC CONCEPTUALIZATION

The development of the geologic and hydrogeologic conceptual model for the 6 CAs has built upon studies previously completed by the OGS, the Geological Survey of Canada (GSC), private consulting companies and conservation authorities. A large component of the study is the review of these previous studies and compilation of the data into a common database and geographic information system (GIS). This is necessary to create seamless mapping products across the study area, which is required for the development of the hydrogeologic model. The MOE's Water Well Information System (WWIS) is one of the primary data sources for the study. The locations of water wells that are completed in either bedrock or overburden, are shown in Figure 31.2. Over 100 000 water wells exist within the study area.

Other data sources that have been compiled to aid in the development of the geologic and hydrogeologic conceptual model include

- digital elevation model
- Permits to Take Water
- geophysical logs
- oil and gas well records
- Quaternary geology reports and maps
- bedrock geology reports and maps
- surface water modelling results and recharge estimates
- numerical models (e.g., MODFLOW) completed from smaller local-scale projects
- stream gauge and spot flow locations and monitoring data
- groundwater levels from Provincial Groundwater Monitoring Network and other monitoring programs
- orthoimagery
- GIS-based base mapping
- land use and cover
- Wetlands, Environmental Site Assessments, and Areas of Natural Scientific Interest

A series of seamless preliminary regional maps were prepared for this study. These maps are listed in Table 31.1.

Table 31.1. Summary of preliminary seamless mapping products.

Seamless Map	Data Source	Comments
Surface Topography	Ministry of Natural Resources	No interpretations required
Bedrock Topography	Ministry of Environment (WWIS)	Natural neighbour interpolation using wells that extend to bedrock
Bedrock Depth		Grid based calculation: [Surface Topography] – [Bedrock Topography]
Quaternary Geology	Ministry of Northern Development and Mines, Ontario Geological Survey	No interpretations required
Bedrock Groundwater Equipotentials	Ministry of Environment (WWIS)	Natural neighbour interpolation using wells that extend to bedrock
Water Well Locations	Ministry of Environment (WWIS)	Wells with poor location or elevation reliability were not included

More than 100 geologic cross-sections have been completed throughout the study area. The cross-sections were interpreted with the selection of geologic contact picks using the following six-layer conceptual model for the study area:

- upper aquifer
- upper till(s) (i.e., St. Joseph, Elma, Stratford, Mornington, Wartburg, Rannoch)
- intermediate aquifer
- intermediate till(s) (i.e., Tavistock, Port Stanley)
- lower aquifer
- lower till(s) (i.e., Catfish Creek, Canning)

In areas where extensive lacustrine clay-rich deposits were present (such as the St. Clair clay plain), this feature was incorporated into the appropriate conceptual layer. This approach was adopted to facilitate subsequent groundwater model development, and was considered appropriate due to the hydrogeologic similarities between the fine-grained tills and lacustrine deposits. Additional cross-sections will be drawn in areas where the stratigraphy is more complex, or where geological features (e.g., kame moraines, eskers, clay plains) should be constrained over a localized area.

FUTURE WORK

It is intended that, in late September 2004, the FEFLOW™ groundwater model will be constructed. In late 2004, the groundwater model will be calibrated using observed groundwater elevation and stream flow data. The calibrated model will be applied to assess groundwater flow rates and water budget components for each of the 6 CAs within the study area. The model will also be used to evaluate different scenarios, which may include drought conditions, urbanization, changes in agricultural practices, and increased groundwater usage.

32. Project Unit 04-032. Gamma-ray Logging of Monitoring Wells in the Upper Thames River Watershed and Surrounding Area

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INTRODUCTION

Under the Groundwater Resource Project (GRP) program, the Ontario Geological Survey (OGS) is funding a project by the Upper Thames River Conservation Authority (UTRCA) to conduct downhole gamma-ray logging of water wells and monitoring wells in the Upper Thames River watershed and surrounding areas of southwestern Ontario (Figure 32.1). The purpose of the study is to collect high quality information that can be utilized to generate a better understanding of subsurface geologic units in the region.

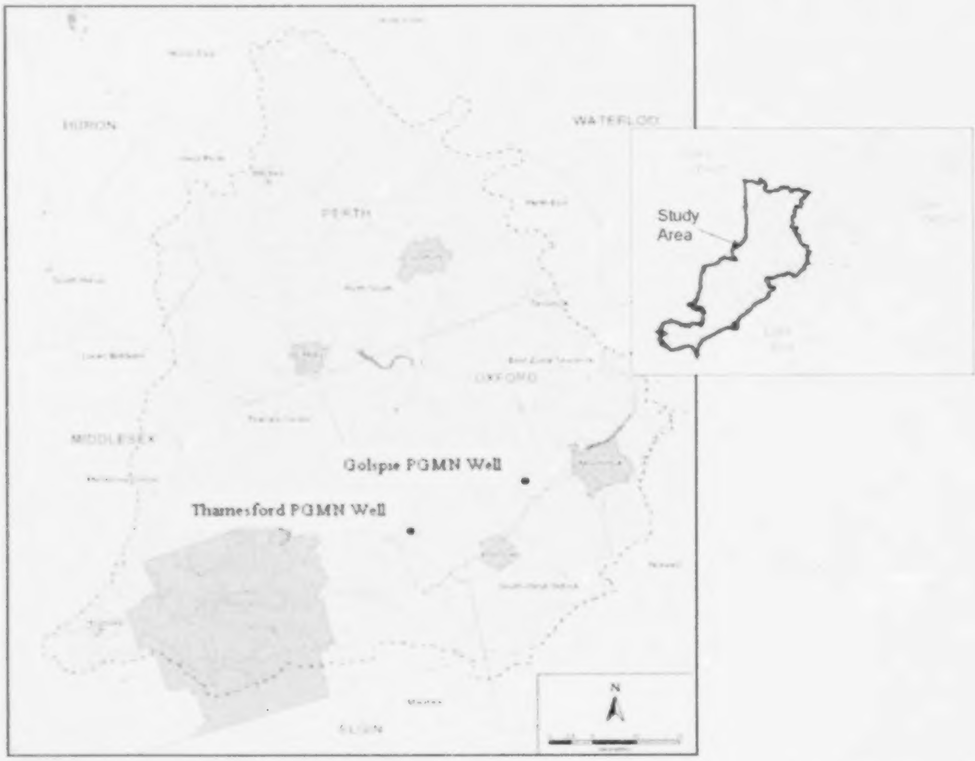

Figure 32.1. Locations of study area (inset map) and upper Thames River watershed with sites of Golspie and Thamesford monitoring wells from the Provincial Groundwater Monitoring Network (PGMN).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.32-1 to 32-6.

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BACKGROUND

The Upper Thames River watershed (*see* Figure 32.1) is situated in a highly developed part of southwestern Ontario and faces pressures from urban and rural land uses. The upper watershed of the Thames River covers 3432 km^2 in southwestern Ontario, includes 17 municipal areas, and 422 322 people reside in the region. Drainage practices, runoff, spills and urban development impact the surface water and groundwater quality of the Thames River and its tributaries.

In 2002, the Ministry of the Environment (MOE) funded a number of municipal groundwater studies relevant to the watershed. By 2004, all counties (Oxford, Middlesex, Elgin and Perth) in the UTRCA watershed had a groundwater model based primarily upon data available through the MOE water well information system (WWIS) database.

Following completion of the municipal studies, it became apparent that some of the aquifers in the UTRCA watershed were regional in extent and extended beyond the municipal and watershed boundaries. Based on these studies, 6 conservation authorities in southwestern Ontario formed a partnership to propose the development of a regional groundwater flow model of their collective watersheds to the OGS (Merry, Nicks and Meyer, this volume). The 6 conservation authorities include the Ausable Bayfield, Essex Region, Lower Thames Valley, Maitland Valley, St. Clair Region and Upper Thames River.

In 2004, the UTRCA also proposed a program of downhole gamma-ray logging to the OGS to obtain high-quality subsurface information on groundwater and aquifers in its watershed as well as those of the other 6 conservation authorities.

GAMMA-RAY LOGGING

The gamma-ray logger is a tool used to measure the natural gamma radiation of overburden or bedrock adjacent to the borehole. Unstable elements or isotopes emit natural radiation in the form of alpha, beta and gamma rays as part of their decomposition, however, it is only practical to measure the gamma rays in a well bore. The gamma-ray logger records the number of photons produced by incident gamma radiation received at a detecting crystal over a period of time. Gamma radiation is a natural substance in the earth that results from the daughter products of decayed uranium-238, thorium-232, and potassium-40 (^{40}K) (Hallenburg 1998).

The count per second value obtained from the gamma-ray logger represents the type of material present at that particular depth. The gamma-ray logger is a useful tool to distinguish between non-porous media (aquitards) and porous media (aquifers), however, it can not be used to give an exact lithologic description. For example, it is difficult to decipher between carbonates such as limestone and dolostone when using the gamma-ray geophysical output alone. The gamma-ray log usually reflects the clay content of the surrounding sediment in the well bore and is assumed to be dominantly the radiation emitted by the ^{40}K contained in the clays. Clays and other fine-grained materials (till, lacustrine clays and shale bedrock) show higher levels of radioactivity than other types of sediment. Clean sand and gravel (outwash deposits) and carbonate bedrock normally exhibit a low level of natural radioactivity. Peat is also characterized by a very low response.

Natural gamma radiation measurement has become an accepted source of information for the definition of vertical profiles. It has been widely used in the petroleum industry for decades and, more recently, in glacial geology and hydrogeology (Bleuer 1986; Nicks 2004). The gamma-ray logger is a versatile tool and is useful in glacial terrain because it is generally a direct indicator of lithology. As previously stated, the log provides an estimate of clay content. This is only a subjective estimate of clay content, however, because other factors affect the gamma-ray readings (e.g., variations in borehole diameter; casing material; grouts, cement or borehole drilling fluids and background noise due to gamma rays emitted naturally as a component of cosmic rays).

The gamma-ray logger can be used in an open or cased hole. Cased holes can be lined with polyvinyl chloride (PVC) or galvanized steel casing that extend above or below the water table. The gamma-ray logger is dependent on a time constant, in which the number of counts is averaged, balanced against the logging speed at which the crystal is passed down the well. The counts and speed of logging vary with the diameter of the well and the nature of the sediments.

The gamma-ray logging project for the UTRCA watershed has been divided into 4 phases:

1. logging of Provincial Groundwater Monitoring Network (PGMN) wells from the 6 conservation authority watershed areas;
2. collecting drill-cutting samples and logging domestic water wells drilled throughout the UTRCA watershed over the duration of the project;
3. drilling 1, 2 or 3 continuously cored, exploration monitoring wells; and
4. development of geologic cross-sections and interpretation of gamma-ray logs in the UTRCA watershed.

The first phase involves the collection of gamma-ray logs from existing monitoring wells. This will enhance the understanding of regional variation in lithology at depth for the UTRCA watershed study as well as support the geological investigation portion of the 6 conservation authority groundwater modelling study. Gamma-ray logs have been collected for the monitoring wells in the UTRCA, Ausable Bayfield, St. Clair Region, Lower Thames Valley and Essex Region watersheds, and are pending for the monitoring wells of the Maitland Valley Conservation Authority.

Several logging systems were investigated, and one system was chosen for its size, reliability and pricing. A Robertson Geologging Limited (RG), United Kingdom, system was purchased by the UTRCA to complete an expected five-month to six-month field season.

The equipment consists of the RG Micrologger2, a 150 m small capacity "RG Mini-Winch", and 2 sondes: the Slimline Natural Gamma Probe and the 38 mm Natural Gamma Sonde. Both sondes have a thallium-activated cesium iodide scintillation crystal inside to record the natural gamma, however, the Slimline has a smaller crystal and is smaller in size. The Slimline Natural Gamma Probe is 45 cm in length with a 2 cm diameter. The 38 mm sonde is 3.8 cm in diameter, approximately 60 cm in length. The larger crystal in the 38 mm sonde will increase the overall counts per second recorded so that the variance in the counts will decrease and will result in a smoother line on the log readout (Figure 32.2). The counts measured are lower in the smaller sonde and the system needs to be operated at a lower speed. However, it allows the inclusion of information from small diameter monitoring wells.

The equipment is mounted in a van and runs off of a 12-volt deep-cycle battery. The components are portable and can be transferred to more remote locations not accessible by vehicle. Equipment setup consists of the RG Micrologger2 connected to the RG Mini-Winch and an IBM® notebook computer, with the sonde connected to the end of the winch cable. The winch cable is positioned over the well by a tripod, which is electronically connected to the winch and records the speed of the cable movement. As the sonde begins to log, the information is sent through the winch cable to the Micrologger2. The data are then recorded using RG Winlogger software, which is designed by Robertson Geologging for log viewing and to control equipment communication.

RESULTS

By the end of August, gamma-ray logs from approximately 40 wells throughout the UTRCA, Ausable Bayfield, St. Clair Region, Lower Thames Valley and Essex Region watersheds had been collected. Locations of monitoring wells in the Maitland Valley watershed have not been provided to date and will likely be obtained at a later time.

Figure 32.3 illustrates the nature of the data. Correlation between individual wells throughout the watershed has not been completed at this time. However, overlapping data from 2 wells located 14 km apart illustrates that correlations can be made.

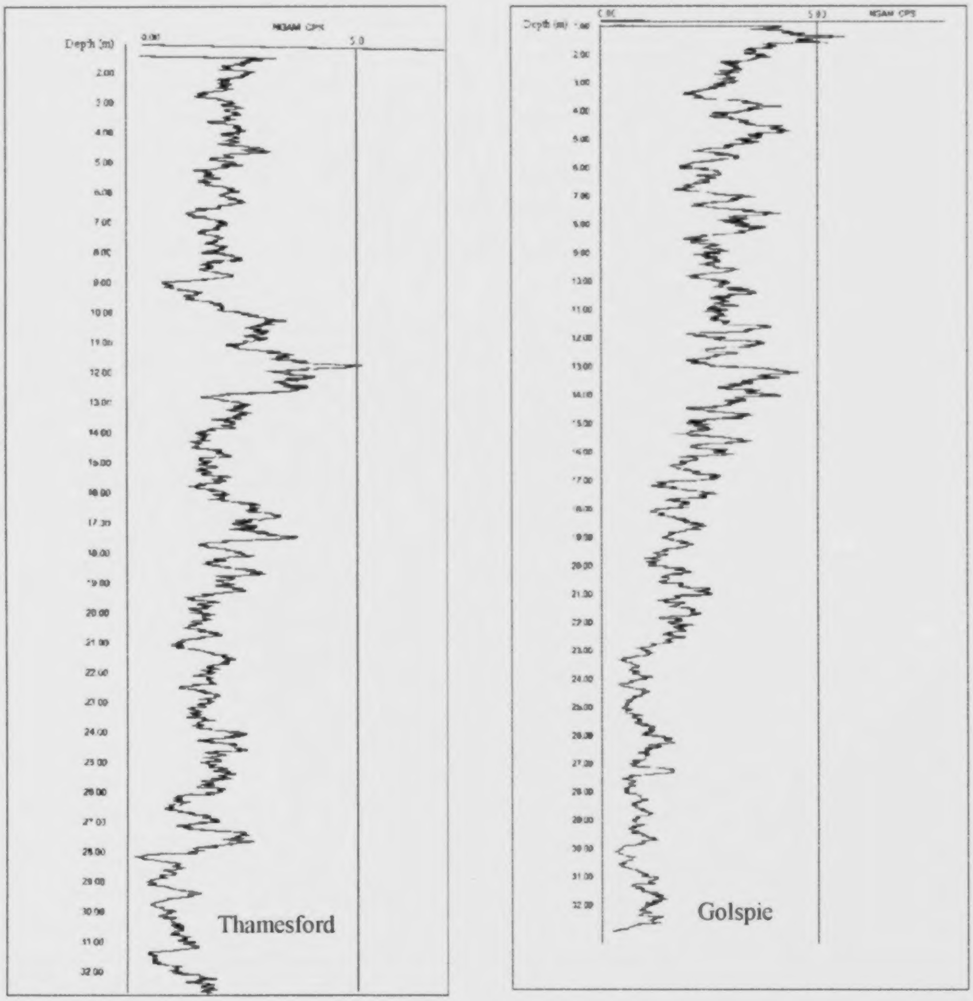

Figure 32.2. Example of gamma-ray logs for 2 PGMN wells in Thamesford and Golspie (for locations, *see* Figure 32.1).

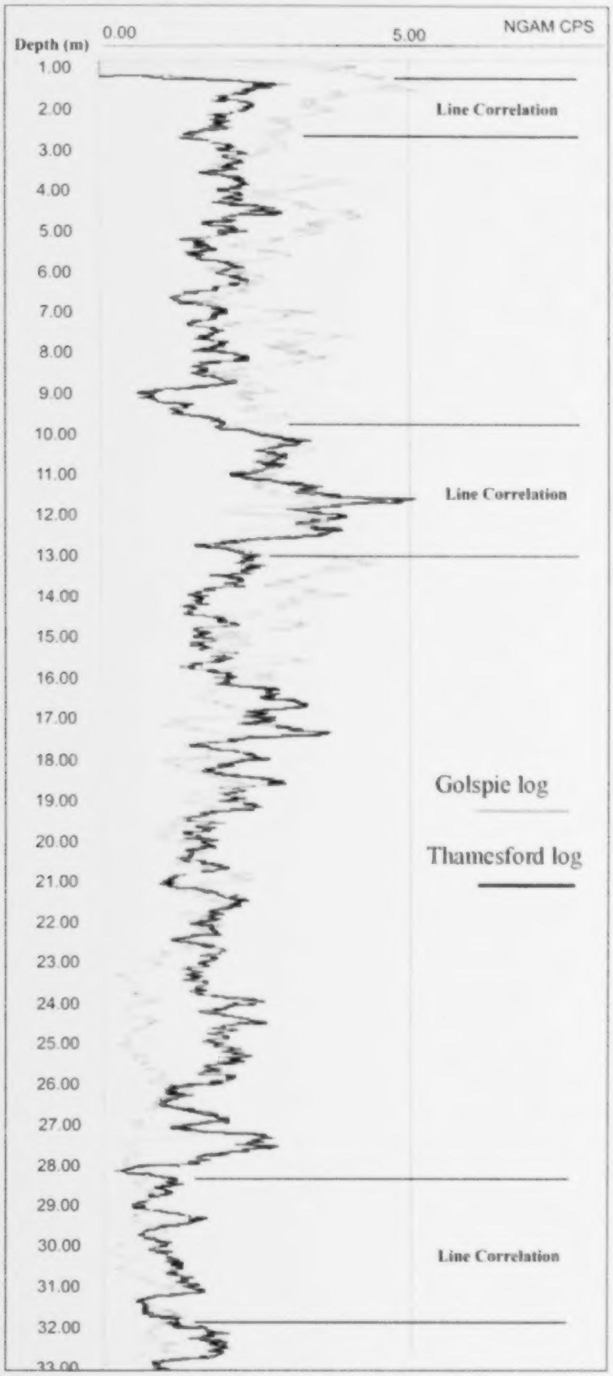

Figure 32.3. Gamma-ray logs for Thamesford PGMN and Golspie PGMN wells overlapped to test for correlation.

FUTURE WORK

Phases 2 and 3 (the collection of samples, cores and gamma-ray logs) will be conducted between September and December, 2004, and the description and interpretation of the data (or Phase 4) will be completed between January and May 2005.

The shape of gamma-ray log curves has long been used by the petroleum industry to interpret depositional facies because the logs reflect grain size. The gamma-ray log is not a measure of grain size *per se*, but of the relative abundance of radioactive elements, which may be related to clay or shale content. The elements measured by the gamma-ray logger are common in clay minerals and, in clastic successions, measurements reflect the "cleanness" (lack of clay or shale) or "dirtiness" (abundance of clay or shale). The log response of a distinctive bed or series of beds can be used to define a marker bed. Marker beds mapped regionally are important stratigraphic surfaces. Diamictons or tills are generally good marker beds.

Pattern matching techniques may be used to interpret vertical facies successions. The bounding surfaces or marker beds may be unconformities or disconformities. Pattern matching is accomplished by correlating log shapes over intervals of a metre to several metres. Pattern matching is extremely useful where the patterns can be correlated to cores and they enhance the interpretation in areas where there are no cores or samples. The vertical profile provided by the gamma-ray logger may be used for regional mapping of facies and recognizable depositional sequences of sediments can be identified in glacial deposits.

At this time, the shape or pattern of the logs has not been calibrated to well-understood glacial depositional facies in the study area. Following the completion of the exploration well(s) and the collection of more samples from wells, a greater understanding of the subsurface geology will emerge. As data collected from drilling continuous cored wells and samples obtained while drilling domestic wells are analyzed, a better understanding of the glacial environment at depth and the hydrogeology will be reached.

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33. Project Unit 04-026. Groundwater Resource Project (GRP) for the Hamilton Area Watershed, Southern Ontario

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INTRODUCTION

Under the Ontario Geological Survey (OGS) Groundwater Resource Project (GRP) program, the Hamilton Conservation Authority (HCA) was provided funding to undertake a study to delineate and characterize the groundwater resources of its watershed area. This two-dimensional groundwater and aquifer mapping exercise is a step towards eventually mapping the three-dimensional subsurface geology of the area.

The HCA is responsible for 479 km^2 of watershed area with a watershed population of almost 400 000 residents (Figure 33.1). Included in this drainage area are Spencer Creek and its tributaries; Borer's, Chedoke, Red Hill, Battlefield, Stoney and Fifty creeks; and several small drainage areas between the Niagara Escarpment and Lake Ontario in the former City of Stoney Creek. These watercourses ultimately drain into Lake Ontario.

BACKGROUND

The Ministry of Environment (MOE) recently funded a groundwater study by a partnership that included HCA, the City of Hamilton, Conservation Halton, Grand River Conservation Authority and Niagara Peninsula Conservation Authority (SNC Lavalin Engineers & Constructors 2004). This study utilized data from the MOE Water Well Information System (WWIS) database and other sources to generate a series of basic two-dimensional thematic surfaces such as water well types, overburden thickness, sand and gravel thickness, bedrock topography and aquifer vulnerability. It also delineated capture zones of municipal wellfields within the study area. The MOE-funded study found that the large majority (approximately 95%) of the study area's population derived its drinking water from Lake Ontario. The remaining 5% of the population (concentrated mainly in the areas south and west of the City of Hamilton) derived its water supply from groundwater sources (SNC Lavalin Engineers & Constructors 2004).

The HCA GRP will build on the MOE-funded study, which had a larger and more populous study area. Field work will attempt to incorporate WWIS data that was discarded because of poor location information. Higher quality technical data, from sources such as geotechnical boreholes, environmental studies and geological mapping, will be added to the database. Particular emphasis will be placed on filling geographical "data gaps" identified in the MOE-funded study.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.33-1 to 33-4.

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The objective of the HCA GRP is to create a more robust database for the Hamilton watershed area, developed upon the existing MOE WWIS database, that will allow the generation of a more complex and comprehensive set of groundwater resource maps. The HCA GRP will also examine the relationship between groundwater systems and geological formations, and the interaction between groundwater and surface water within the Hamilton watershed.

EXAMINATION OF DATA FROM THE WATER WELL INFORMATION SYSTEM (WWIS) DATABASE

The MOE WWIS database contains data from 6168 water wells in the HCA watershed area. Of these, 2918 water wells have unreliable geographical co-ordinates (i.e., the margin of error is estimated to be greater than 300 m). Initially, field work was planned to locate and properly georeference as many as these water wells as possible. However, most of the data in the WWIS database are derived from water well contractors, most of whom have little to no formal geoscience training or expertise. It was recognized that the geoscience data in the WWIS database is of limited utility; as such, it was decided that the focus would be shifted to the acquisition and evaluation of higher quality geoscience data.

ACQUISITION OF HIGHER QUALITY TECHNICAL DATA

"Higher quality technical data" includes data generated from established technical and scientific methodologies (e.g., downhole geophysical instrumentation) and data generated by a professional geoscientist or professional engineer (e.g., borehole logs from monitoring well installations). It should be noted that the MOE-funded study also includes some higher quality technical data, including borehole logs from quarrying operations and environmental site assessments (SNC Lavalin Engineers & Constructors 2004).

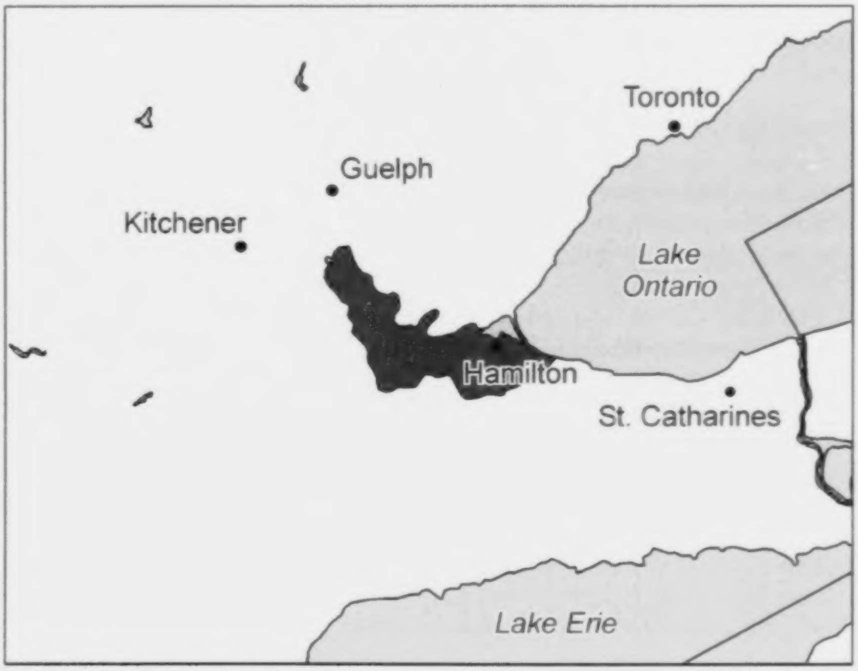

Figure 33.1. Location of the study area.

Table 33.1. Location reliability of boreholes within the HCA watershed boundaries from a published urban technical database (*after* Bélanger and Morin (1995)).

Reliability Code	Number of Boreholes within the Study Area
Excellent	4332
Good	2873
Fair	3727
Poor or Unknown	8010

Table 33.2. Sources of technical data, including borehole logs, compiled and added to the HCA GRP database (*after* SNC Lavalin Engineers & Constructors (2004)). The data will be used to provide a more comprehensive evaluation of groundwater resources within the HCA watershed.

Data Source	Number of Boreholes within HCA Study Area
Groundwater Resources of the Township of Puslinch	407
Red Hill Valley Project	185
Landfills (Brow, Taro West, Ancaster, Stoney Creek, Dundas, West Hamilton Closed, Smith Enterpise and Upper Ottawa)	120
Subdivisions (Geotechnical Investigation, GW Assessment, Env. Assessment and Slope Stabilty, etc.)	591
Quarries (Flamboro, Taro East & West, Vinemount Quarry)	69
McMaster Campus Borehole Report	32
Storm Water Management Studies	42
Ministry of the Environment - Contamination Site Studies	127
Ministry of Transportation (borehole and wells)	780
Urban Geology Database for Hamilton Region (GSC)	5234
City of Hamilton – Borehole Inventory (mainly 1800 geotechnical investigations reports in PDF format)	500(estimate)

The HCA GRP acquired an urban technical database for the Hamilton region (Bélanger and Morin 1995), which contains 5 relational databases describing the subsurface, soil properties, stratigraphy, and water tables for borehole logs in the Hamilton Region. The urban technical database contains data on many boreholes, 18 942 of which are within the HCA watershed boundary. Of these 18 942 boreholes, 7205 (or 38%) are indicated as having "excellent" or "good" location reliability codes (Table 33.1).

The HCA GRP also incorporated data into its database from technical reports compiled by the MOE-funded Hamilton-area study (SNC Lavalin Engineers & Constructors 2004). A summary of these data is provided in Table 33.2.

In addition to the above data, HCA employed 3 summer students to compile data from information files of the local offices of the MOE, HCA, Ministry of Transportation and City of Hamilton. All pertinent information from borehole records was extracted and input into the HCA database. Information entered included well construction information, overburden and bedrock descriptions, aquifer properties, engineering properties and water quality information. Quality control of the data was provided by randomly reviewing data entered into the database against the original borehole records to ensure consistency of data entry and reliability of entered data.

FUTURE WORK

Data compilation and entry into the HCA database will continue. Upon completion of data compilation, the HCA database will be used to generate a series of thematic map surfaces of the Hamilton watershed similar to that of the MOE-funded study (SNC Lavalin Engineers & Constructors 2004). In total, 12 map surfaces will be generated from geographic information system (GIS)-based point source and interpolated data. The map surfaces will be evaluated to provide a better understanding of the groundwater systems, and to develop conceptual geological and hydrogeological models of the Hamilton watershed.

The Hamilton Conservation Authority will also investigate the incorporation of the data model that is currently being utilized for the York–Peel–Durham–Toronto (YPDT) groundwater study (Earthfx Incorporated 2003). Discussions will be held on methods to adopt this data model for the HCA GRP.

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34. Project Unit 03-025. Nutrient Management Project: Characterization of Fractured Paleozoic Bedrock in Thin Drift Areas of Southern Ontario

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INTRODUCTION

As part of ongoing provincial initiatives to protect the quality of soil and water in Ontario, the *Nutrient Management Act 2002*, S.O. 2002 was enacted. The Act, administered by the Ministry of Agriculture and Food (OMAF) and the Ministry of the Environment (MOE), provides guidelines for the application of agricultural (e.g., solid and liquid manure) and non-agricultural (e.g., pulp and paper and sewage biosolids) source material to soils. The Ontario Geological Survey (OGS) is working with OMAF to characterize thin surficial materials and near-surface bedrock to aid in the development of regulations under the Act. A significant portion of Ontario's agricultural land is underlain by thick overburden (>1 m), which generally provides an effective zone of attenuation for nutrients carried in downward-migrating surface waters. However, a number of agricultural areas are located in regions with a thin cover of surficial materials (<1 m to bedrock). In these areas, the thin soil cover may not provide sufficient protection, allowing nutrient-enriched waters to enter fractures in the underlying bedrock and proceed unimpeded into the groundwater system.

The project is currently in the 2nd year of a two-year study designed to investigate agricultural areas of southern Ontario which are characterized by a thin cover of surficial material over Paleozoic bedrock. In addition to the 3 areas studied in 2003, a fourth area centred around Smiths Falls and 7 sites underlain by Precambrian rocks in the Gananoque area were added for field investigation this year (Figure 34.1).

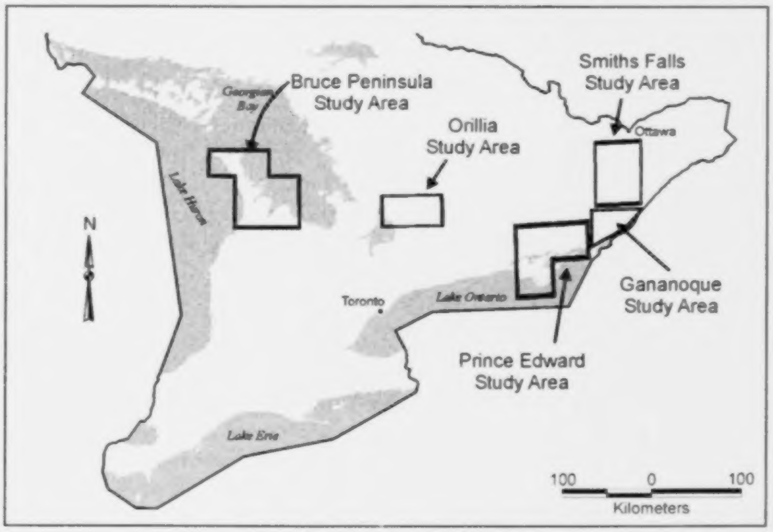

Figure 34.1. Location of study areas.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.34-1 to 34-7.

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34. Project Unit 03-025. Nutrient Management Project: Characterization of Fractured Paleozoic Bedrock in Thin Drift Areas of Southern Ontario

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INTRODUCTION

As part of ongoing provincial initiatives to protect the quality of soil and water in Ontario, the *Nutrient Management Act 2002*, S.O. 2002 was enacted. The Act, administered by the Ministry of Agriculture and Food (OMAF) and the Ministry of the Environment (MOE), provides guidelines for the application of agricultural (e.g., solid and liquid manure) and non-agricultural (e.g., pulp and paper and sewage biosolids) source material to soils. The Ontario Geological Survey (OGS) is working with OMAF to characterize thin surficial materials and near-surface bedrock to aid in the development of regulations under the Act. A significant portion of Ontario's agricultural land is underlain by thick overburden (>1 m), which generally provides an effective zone of attenuation for nutrients carried in downward-migrating surface waters. However, a number of agricultural areas are located in regions with a thin cover of surficial materials (<1 m to bedrock). In these areas, the thin soil cover may not provide sufficient protection, allowing nutrient-enriched waters to enter fractures in the underlying bedrock and proceed unimpeded into the groundwater system.

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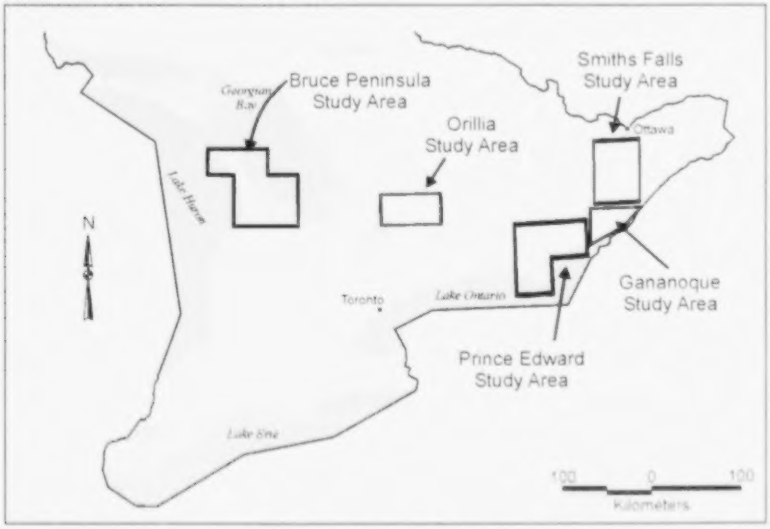

Figure 34.1. Location of study areas.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.34-1 to 34-7

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Field work in the summer of 2003 (Strynatka 2003) focussed on assessing physical properties of overburden (field saturated hydraulic conductivity, bulk density, particle size) in the thin drift areas. These areas were identified from the Surficial Geology of Southern Ontario (SGSO) digital Quaternary geology compilation (Ontario Geological Survey 2003). Work in the 2004 field season took place between June 6 and August 20, and focussed solely on attempting to characterize the nature of fractured Paleozoic bedrock in the thin drift areas.

PROJECT LOCATIONS AND GEOLOGY

At a regional scale, areas of thin drift over Paleozoic bedrock were identified in ESRI® ArcMap™ 8.3 by querying the SGSO compilation (Ontario Geological Survey 2003) for areas with a primary material identified as "Paleozoic Bedrock". These areas consisted of exposed bedrock, or bedrock covered by a thin (<1 m), discontinuous layer of drift. In some areas, agricultural (cropland, pasture) shapefiles from the Ontario Land Classification Database (Spectranalysis 1999) were used to refine the selection of areas for investigation.

The Bruce Peninsula study area is represented on National Topographic System (NTS) map sheets 41 A/10, 41 A/11, 41 A/14, 41 A/15, 41 H/03 and 41 H/04. Bedrock in this area consists primarily of dolomitic rocks of the Silurian-aged Guelph and Amabel formations. The underlying stratigraphy (Silurian-age Fossil Hill, St. Edmund, Wingfield, Dyer Bay, Cabot Head, and Manitoulin formations, and the Ordovician Queenston and Georgian Bay formations) is exposed at various locations along the eastern side of the peninsula. Karst and dissolution features such as surface pitting (pitkarren) and grike-and-clint (kluftkarren, Photo 34.1) are well developed within the Bruce Peninsula survey area (Armstrong and Dubord 1992).

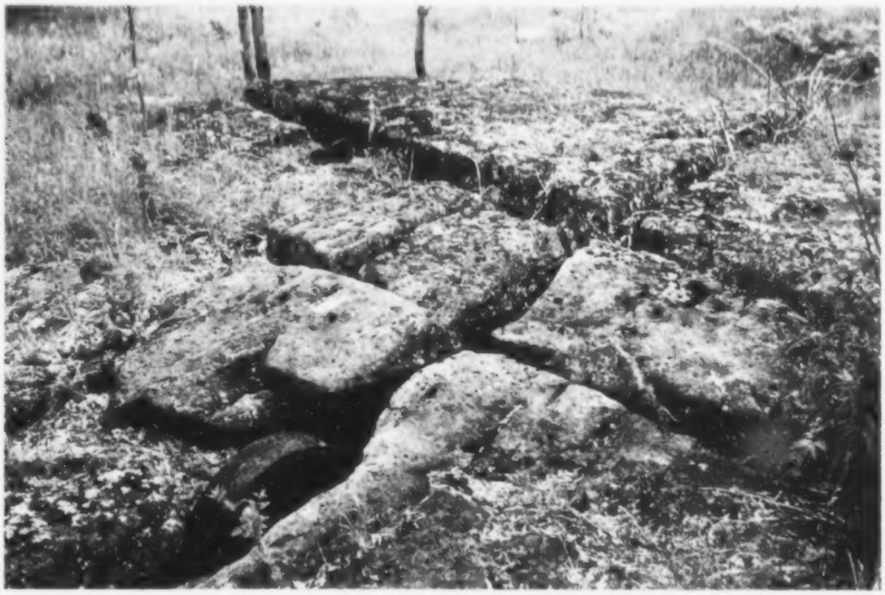

Photo 34.1. Well-developed kluftkarren, Amabel Formation dolostone, Keppel Township, Bruce Peninsula.

The Orillia study area covers the Carden limestone plain and is represented on NTS maps sheets 31 D/10 and 31 D/11. Bedrock geology in this area consists of limestone and limestone–shale units of the Verulam, Bobcaygeon and Gull River formations, shale and sandstone rocks of the Shadow Lake Formation (all of Ordovician age), and Precambrian rocks belonging to the Central Gneiss and Central Metasedimentary belts (CGB and CMB) of the Grenville Province (Armstrong and Anastas 1993; Armstrong and Rhéaume 1994). Kluftkarren was observed at several sites within this area, primarily within the lower member of the Bobcaygeon Formation.

The area referred to in Strynatka (2003) as the Prince Edward County study area also includes the southern parts of Hastings, Lennox and Addington, and Frontenac counties, and will be abbreviated herein as the PHLF study area. This area is represented on portions of NTS map sheets 30 N/13, 30 N/14, 31 C/02, 31 C/03, 31 C/06, and most of 31 C/07. North of the Bay of Quinte, the dominant lithological units in the study area are eastward extensions of the Bobcaygeon and Gull River formations found in the Carden limestone plain. To the south in Prince Edward County, bedrock geology consists primarily of nodular limestone and shale of the Lindsay Formation with lesser amounts of the underlying Verulam Formation (Carson 1980, 1981a, 1981b, 1981c). The nodular and shaly nature of the Lindsay Formation (Photo 34.2) often weathers to form a rocky, clay-rich soil that obscures bedrock structural features at the surface. This type of soil can be observed throughout the county. Kluftkarren and groove karren (solution enhancement along horizontal planes) are well developed within this area as well, particularly in the upper member of the Gull River Formation, north of the Bay of Quinte.

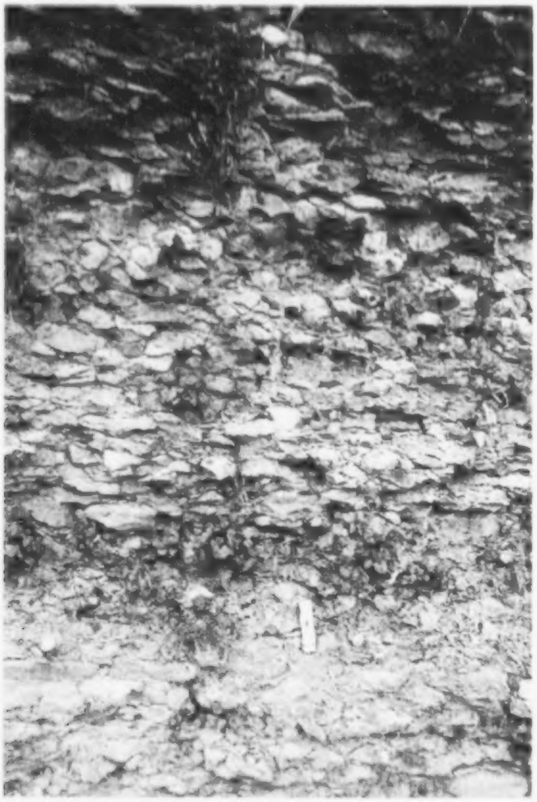

Photo 34.2. Nodular shaly limestone, upper Lindsay Formation, Hallowell Township, Prince Edward County.

The Smiths Falls study area, centred roughly halfway between Kingston and Ottawa, is located on the northeast side of the southeast-trending Frontenac Arch. The Frontenac Arch is a regional upland consisting of Mesoproterozoic rocks of the CMB. Paleozoic rocks in the Smiths Falls area are stratigraphically lower than those of the other study areas, consisting primarily of dolostone, sandstone and sandy dolostones of the lower Ordovician Oxford and March formations and the Cambro-Ordovician Nepean Formation (sandstone) (Carson 1982a, 1982b; Williams and Wolf 1984a, 1984b, 1984c). Unlike the other 3 locations, the north part of this area is marked by extensive faulting. The normally flat-lying strata often dip steeply adjacent to faulted areas and within fault zones (Williams and Wolf 1984b). Karst features are not as prevalent in this area as in the previous 3 areas. Some kluftkarren were observed at sites in the Gull River and March formations.

The sites examined in the Gananoque area are underlain by Paleo- to Mesoproterozoic rocks consisting of paragneiss, quartzofeldspathic gneiss, marble and quartz arenite (Easton 1992). As expected, the nature of fracturing within these rocks differs from that of the horizontally bedded Paleozoic rocks. Vertical fracture sets do occur, although jointing is just as likely to be shallow to steeply dipping. Unlike the laterally continuous limestones, dolostones and shales, abrupt lithological changes were observed to occur over small distances (<250 m). No evidence of solution features were observed at any of these sites.

METHODOLOGY

Near-surface bedrock joint characterizations were obtained from surface pavements, road cuts and quarries, using protocols outlined in Barton (1981) and followed by Strynatka (2003). At each outcrop, the following measurements and features were noted:

- Universal Transverse Mercator (UTM) coordinates recorded with a Garmin® GPS 12XL™ global positioning system
- Brief location and site description
- Joint set spacing (total number of joints over the distance the set was exposed in a direction perpendicular to the average strike of the set)
- Strike of individual joints (indicated as 0 to 180°), dip where present
- Joint aperture
- Joint roughness
- Filling material
- Length of joint trace
- Termination (off outcrop or under overburden, within rock or against another joint)
- Degree of moisture seepage or flow, if observed
- Degree of karsting and/or dissolution, if observed

In quarries and at road cuts, notes were made on the thickness of the observed bedrock unit(s), as well as the spacing between horizontal fractures (bedding plane fractures and/or parting surfaces). Observations were also made of the vertical extent (depth) of observed fractures.

Field notes were recorded on waterproof Duksbak™ paper. Digital photographs were taken at each site to supplement notes taken and to document unique features of each site.

PRELIMINARY OBSERVATIONS AND RESULTS

Soil Permeability

During the 2003 field season, measurements of field-saturated hydraulic conductivity were conducted using the Guelph Permeameter method of Reynolds and Elrick (1985). Across the 3 areas investigated measurements ranged from 2.93×10^{-5} cm/s (<5 cm/day) to 3.02×10^{-2} cm/s (>20 m/day). These measurements occurred in a variety of soil types ranging from sandy loams to clay-rich soils, and suggest that regardless of soil type, the residence time of downward-migrating surface waters in thin soils may be insufficient for incorporation or attenuation of applied nutrients; that is, nutrient-enriched surface waters stand a good chance of reaching bedrock, where they may progress through fractures into the groundwater system with little to no moderation.

These results prompted the decision to focus solely on the characteristics of fractured bedrock in the 2004 field season. As such, no soil permeability measurements were taken in the Smiths Falls study area.

Bedrock Characteristics

In general, fracture sets observed in the Paleozoic rocks across all study areas are vertical to sub-vertical (85 to 90°), though locally they may exhibit dips varying from 60 to 85°. Individual fractures may have continuous depths in excess of 10 m, may simply terminate within the rock, or may be connected to additional vertical fractures at depth by way of horizontal bedding-plane fractures.

Not surprisingly, fracturing within local areas was observed to be heterogeneous. As an example, at the Essroc quarry near Picton, Prince Edward County, 2 field stations (Station 57 and 58) were located approximately 750 m apart. Common to both locations was a fracture set with an average orientation of 130°, and spacing between fractures of 8.5 m (Station 57) and 8.9 m (Station 58). At Station 57, a fracture set with an average orientation of 66° has spacing between fractures of 3 m (9 fractures observed over 24 m). This set was not observed at Station 58, however a set oriented at 14° was present with spacing of approximately 19 m between fractures. Both of these stations were located in the lower Lindsay Formation identified by Carson (1981b) as a limestone with shaly partings. It should be noted that Station 57 was located in an area of the quarry where bedrock had been exposed at the surface for a number of years, while the rock at Station 58 had only recently been cleared of overburden. While weathering processes may influence the development of existing fractures, it is unlikely to account for the difference in fracture density, and certainly not orientation. The observed differences at these 2 closely spaced sites hint at the heterogeneities present in a natural system and the potential differences in permeability of surficial bedrock over relatively small distances.

In the course of carrying out field work during the past summer, it became apparent that while quarries and road cuts may provide an excellent window into the nature of bedrock up to several tens of metres below surface, they are not necessarily the best sites for performing studies of this nature. Many of these sites use explosives to extract and remove rock. The result is a highly fractured face which is not likely to reflect the natural state of fracturing in the rock. Care must be taken when making observations in these sites to attempt to separate what are likely to be natural fractures (though possibly enhanced by blasting) from those fractures which have been induced by explosives (Photo 34.3). Notable exceptions are dimension stone quarries, particularly on the Bruce Peninsula. Many of these operations use less disruptive extractive techniques such as saws, forklifts and pry bars, thereby preserving the natural state of the rock.

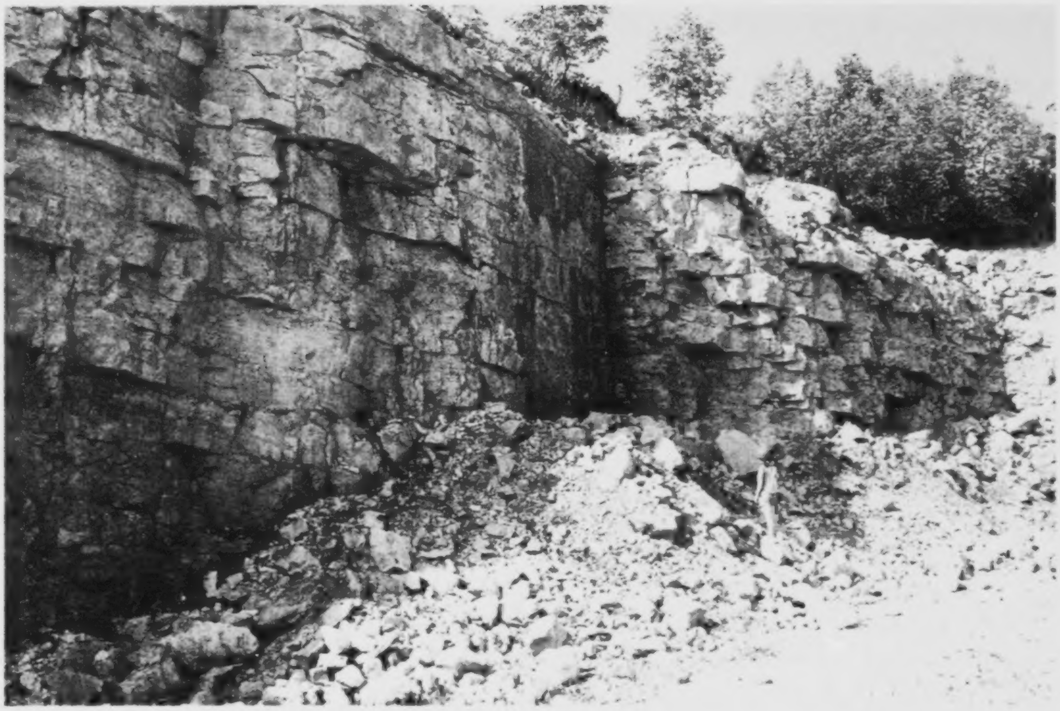

Photo 34.3. Natural joint in blasted bedrock, E.C. King Sydenham quarry, Sydenham Township, Bruce Peninsula.

FUTURE WORK

The goal of this project is to generate a system for characterizing the fractured Paleozoic bedrock observed in southern Ontario. Further compilation and analysis of field observations, as well as ongoing consultations with OMAF will determine the scale of characterization (e.g., regional scale, by bedrock unit, lithology, etc.). Ultimately, this information will be used to help develop regulations for the application of nutrients to soils in Ontario, and in doing so, aid in protecting the quality of Ontario's soil and water resources.

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35. Project Unit 03-021. Three-Dimensional Mapping of Quaternary (Surficial) Deposits in the Barrie Area, Central Ontario

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INTRODUCTION

Pressures directed at protecting and preserving Ontario's groundwater resources have increased greatly over the past few years. At the present time, approximately 3 million Ontario residents depend on groundwater for their drinking water (Ministry of the Environment 2001). Additional pressure is placed on the sustainability of water resources by the residential, commercial and industrial sectors. Many communities, such as the City of Barrie, rely exclusively on groundwater extracted from aquifers that are under or near agricultural or urban areas. The protection of existing resources through careful land-use planning in urban areas and nutrient management practises in rural areas as well as the identification of new groundwater aquifers is critical.

A critical component of mapping groundwater aquifers is a thorough understanding of the three-dimensional stratigraphy of Quaternary (surficial) sediments. These sediments form recharge and discharge zones, local and regional aquitards and producing aquifers. Accurate three-dimensional models will allow new aquifers to be located and the determination of volume of both new and existing groundwater resources. Of equal importance, the models can be used to identify potential pathways for aquifer contamination.

The key objective of the current study is to construct a three-dimensional geologic model of Quaternary sediments in the Barrie area (Figure 35.1). This model will be based on new sonic drilling and associated downhole geophysics, new seismic surveys, pre-existing drilling logs, water well records, published surficial maps and the interpretation of natural and man-made exposures.

LOCATION

The study area encompasses approximately 1200 km^2 between Georgian Bay and Lake Simcoe and is centred on the Oro Moraine (Bass Lake kame moraine, Oro sandhills) located north of the City of Barrie (*see* Figure 35.1). Portions of 5 townships, Innisfil, Oro–Medonte, Ramara, Severn and Springwater, represented on 1:50 000 scale NTS map sheets 31 D/5, 31 D/11 and 31 D/12, are included within the study area.

Major water bodies include Lake Couchiching in the northeast, Kempenfelt Bay (Lake Simcoe) in the south and east, and Bass Lake in the centre of the study area. The metropolitan areas of Barrie, on Kempenfelt Bay, and Orillia, on Lake Couchiching, are the largest urban centres within the study area and have a combined population of nearly 200 000 people.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.35-1 to 35-5.

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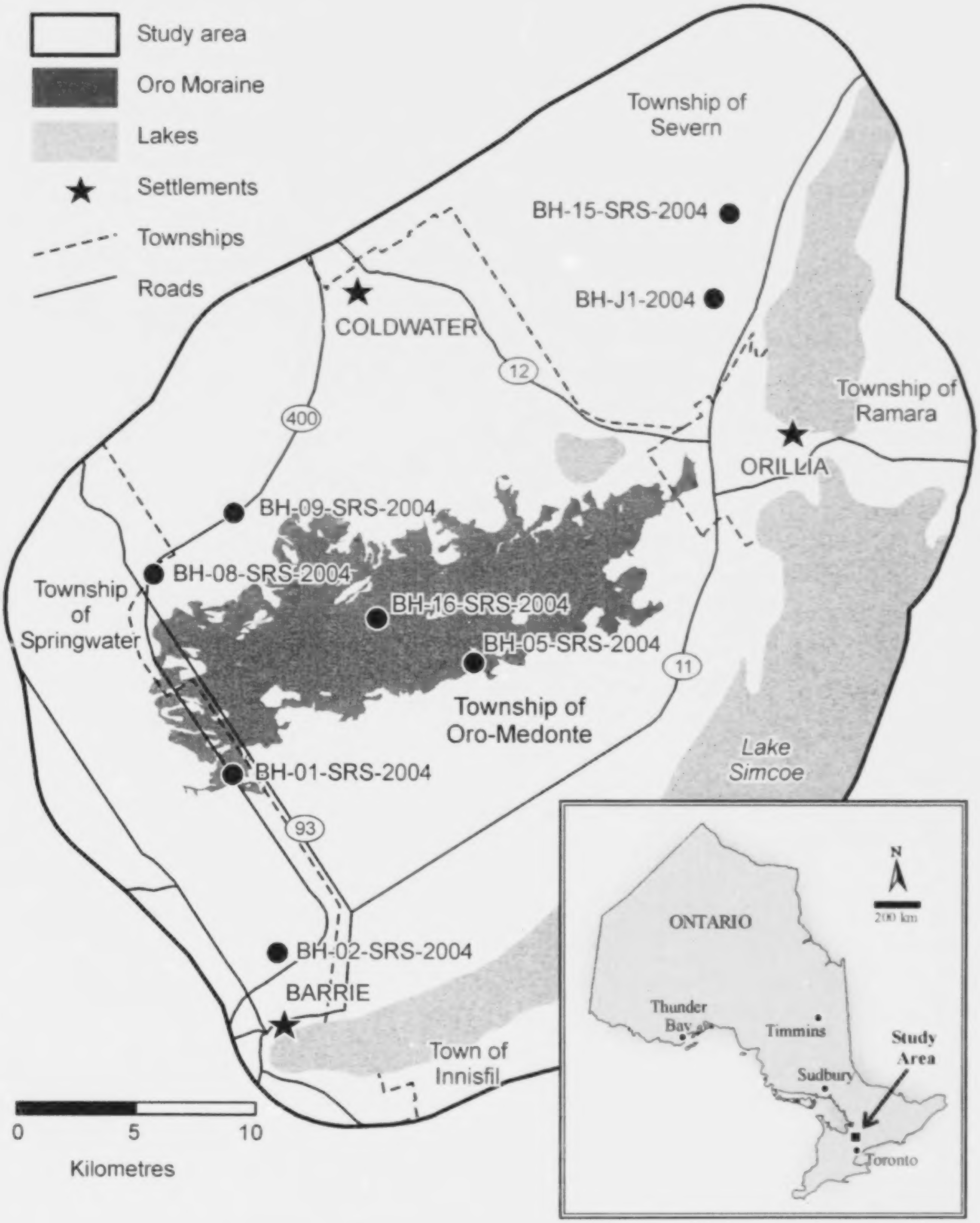
Study area
Oro Moraine
Lakes
Settlements
Townships
Roads
Township of Severn
BH-15-SRS-2004
BH-J1-2004
COLDWATER
12
400
Township of Ramara
ORILLIA
BH-09-SRS-2004
BH-08-SRS-2004
Township of Springwater
BH-16-SRS-2004
BH-05-SRS-2004
11
Township of Oro-Medonte
Lake Simcoe
BH-01-SRS-2004
93
BH-02-SRS-2004
BARRIE
Town of Innisfil
0
5
10
Kilometres
N
200 km
ONTARIO
Thunder Bay
Timmins
Sudbury
Study Area
Toronto

Figure 35.1. Location and boundary of the study area. The Oro Moraine, shown in dark grey, is the most prominent landform within the study area. Borehills drilled from August to September 2004 are indicated.

BEDROCK GEOLOGY

The bedrock geology of the study area is dominated by Middle Ordovician rocks. Shadow Lake Formation sandstone and arkose unconformably overlie Precambrian rocks. The Shadow Lake Formation is in turn overlain by the Simcoe Group, which consists of the Gull River, Bobcaygeon and Verulam formations. These formations are composed of argillaceous and sublithographic or lithographic limestone and calcarenite with minor mudstone and claystone (Liberty 1969).

Proterozoic rocks of the Grenville Province lie north of the Black River Escarpment, which is found in the far north of the study area (Ontario Geological Survey 1991). Layered biotite gneiss and migmatite, quartzofeldspathic gneiss, orthogneiss and paragneiss crop out around the northern tip of Lake Couchiching, whereas tonalite, granodiorite, monzonite, granite, syenite and derived gneisses are found to the west.

Bedrock outcrops are confined to the northern part of the study area.

SURFICIAL GEOLOGY

The sediments and landforms seen across the study area are the result glacial advances and retreats during the Late Wisconsinan Substage. Various till units are found throughout the study area. The Lake Simcoe lobe covered the study area during the Port Bruce Stade, and most likely deposited 3 of the 4 till units present in the study area. The lowermost till is the stoney sandy silt to silt Bogarttown Till, which is rarely exposed in the study area (Gwyn 1972). This is overlain by an unnamed stoney sand till and the calcareous silt to sandy silt Newmarket Till (Barnett 1992, 1997; Gwyn 1972). The study area was ice free during the Mackinaw Interstade, circa 13 300 years BP (Dreimanis 1977). Subsequent Lake Simcoe Lobe ice advances during the Port Huron Stade, circa 13 000 years BP, deposited the highly calcareous silty clay to clay Kettleby Till (Gwyn 1972).

The most prominent feature of the study area is the Oro Moraine which extends from Bass Lake westward to Highway 400 (Figure 35.1). This feature has a hummocky to rolling surface and is approximately 165 km^2 in size. The moraine has been interpreted as an end moraine formed during a standstill of the Lake Simcoe lobe (Deane 1950), an interlobate moraine overridden by ice from the Lake Simcoe basin (Gravenor 1957), a remnant deposit of an earlier sandy moraine built by the Georgian Bay lobe that was subsequently overridden from the northeast (Chapman and Putnam 1984) and an interlobate subaqueous fan with the main sediment supply coming from the south (Barnett 1986, 1988, 1989). Most recently, the moraine has been interpreted as a series of stacked subaqueous fans that exhibit south to southwest paleoflow directions (Slattery 2003). The moraine is composed of stratified coarse- and fine-grained sediments that may form important aquifers and aquitards and as such is of considerable interest in the exploration for groundwater.

Of equal interest are a series of steep-walled valleys located on the western side of the study area (Barnett 1986, 1988, 1990). These valleys are likely tunnel-channels that were incised into basal sediments by the rapid release of ponded subglacial meltwater (Barnett 1986; Brennand and Shaw 1994). These valleys may form groundwater pathways and storage areas.

Glacial outwash, fine-grained glaciolacustrine sediments and glaciolacustrine beaches and bars were deposited in glacial Lake Algonquin after the ice had withdrawn from the study area. The majority of shoreline features within the study area are related to the main level of glacial Lake Algonquin. Higher level shoreline features may be related to early glacial Lake Algonquin or glacial Lake Schomberg (Finamore 1981; Finamore and Bajc 1984; Chapman and Putnam 1984; Barnett 1997).

Postglacial deposits are limited within the study area. Organic deposits consisting of peat, muck and marl are found in low lying areas typically adjacent to lakes and wetlands. Modern alluvium is found in generally narrow bands along the floodplains of many rivers and streams.

PROJECT STATUS

Field work completed to date includes drilling, geophysical surveys and the description of pit and natural exposures. Eight sonic boreholes, totalling 725 m, have been drilled, logged in the field and sampled for carbonate content and grain size analysis (*see* Figure 35.1). Monitoring wells with 1.5 m screens have been installed by the Lake Simcoe Conservation Authority at selected boreholes. A further 5 sonic boreholes with estimated depths of 135 m each are planned for completion in late 2004. Six, approximately 1 km long, seismic surveys have been completed by a contract geophysical company and the results are currently being processed. The Geological Survey of Canada (GSC) also completed a total of 7.5 km of seismic line during the summer of 2004 using its Mini Vibe system. In addition, downhole geophysics will be done at completed boreholes by the GSC.

Data from new boreholes and geophysical records will be used to supplement a subsurface database of water wells and older drilling logs. A three-dimensional model of Quaternary sediments, composed of a series of surfaces including bedrock, tills and coarse- and fine-grained stratified glacial sediments, will be generated using this database. Thus far, the database has been assembled and work has begun on identifying key units.

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Geoscience Program Initiative

36. Ontario Mineral Exploration Technologies (OMET) Program

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INTRODUCTION

Announced by the Ministry of Northern Development and Mines in September 2000, the Ontario Mineral Exploration Technologies (OMET) Program is a four-year, $8.0 million initiative to develop and test innovative mineral exploration technologies and methods. The goal is to enhance the efficiency of the exploration firms in high potential geological areas of Ontario. The OMET program was extended for an additional year to ensure receipt and publication of final reports and final reporting on the OMET program. No new funds projects will be approved during this administrative year. OMET is near the end of the second quarter of the administrative year. Significant progress has been achieved in the past 4 years with the approval of 25 projects for funding. The new technologies and methods developed will increase Ontario's attractiveness to mining and mineral exploration by funding high-potential projects that are targeting Ontario's mineral exploration challenges.

As at June 30, 2004, approximately $6.1 million had been awarded to projects that have undergone assessment reviews and approval recommendation by the Expert Technical Advisory Committee (ETAC). Funding for the program totalled $7,250,000 of the original $8.0 million.

It became evident this year that the one year confidentiality period on each OMET project was going to fall in the year following the program end date. To ensure all project accounting and publication of the research data are completed as initially planned, OMET administration will continue to operate until March 31, 2005, when the program will be wound up.

PROPOSAL SUMMARY

Table 36.1 summarizes the 25 approved proposals indicating the project goals, the exploration challenges being addressed by the researcher, and the expected direct impact the projects will have on the Ontario mineral exploration sector. A brief description is presented to assist in the understanding of the scope of research being carried out by the participants in the OMET program.

Table 36.1. Approved OMET projects.

Proposal #, Name and Title	Project Goals	Exploration Challenge Addressed
P01-02-001 Camiro **Detectability of mineral deposits with airborne gravity**	To model ore deposit responses from airborne gravity data.	The challenge is to refine the target-discrimination potential of airborne gravimetry. This research will further the understanding of: the expected responses of economic targets, the masking of geological noise, the detectability versus depth relationship, and the system specifications of airborne gravity instruments for detection of ore bodies.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.36-1 to 36-6.

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Table 36.1. continued

Proposal #, Name and Title	**Project Goals**	**Exploration Challenge Addressed**
P01-02-002 Camiro **Three dimensional surficial geochemistry**	To determine by field trials the form of metal transport that is most likely to be at work for a given area. The result being to lower sample densities and to lower the number of test parameters.	Surficial geochemistry in areas of thick overburden cover has always presented a challenge to mineral exploration. By systemically studying the natural processes at work at selected sites, the sampling effectiveness and mineral discovery rate in overburden areas will be enhanced.
P01-02-003 Camiro **The use of soil gas hydrocarbon technique to differentiate barren from ore-bearing conductors**	Through laboratory experiments, determine which organic compounds are related to which ore type. Field studies will sample B-horizon soils over different types of conductive bodies. Comparison will be made between the controlled laboratory studies and field studies.	The challenge for explorationists is to distinguish between barren electromagnetic conductors and ore-bearing electromagnetic conductors. The project is expected to provide an effective and cost efficient tool for locating and distinguishing between ore types.
P01-02-007b Geotech **Modeling, interpretation methods and field trial of an existing prototype AFMAG system**	To develop and test by field trials an extremely low frequency (ELFMAG) with high sensitivity multiple-frequency digital system for airborne and ground surveys.	Thick conductive overburden and Paleozoic cover rocks have presented a barrier to traditional electromagnetic methods. This method is expected to provide the capabilities to look deeper at acceptable costs. It will have the potential to map conductive bodies to depths of 1000 m.
P01-02-008a GSC **Three dimensional geochemistry in the Abitibi**	To develop and document a soil geochemical technique for the Abitibi Clay Belt to locate base metal and gold deposits.	The Abitibi Clay Belt with thick and exotic cover has resulted in costly exploration work in the area. The clarification and identification of element migration pathways and fixation in the near surface will allow explorers to locate base metal and gold mineralization through tens of metres of glacial sediments in a cost-effective manner.
P01-02-011a Ferra Dynamics **Technology development of a high bandwidth helicopter EM system**	To test a concept to triple the sample density of helicopter electromagnetic (HEM) system in order to more accurately map glacial sediments and identify conductive bodies underneath them.	Conductive sediments in many regions of Ontario have masked the electromagnetic responses of conductive ore-bearing rocks. This research project will develop, test and prove the acquisition technology so that commercial surveys may be flown using this technology. The technology will be a step toward a basis of one capable of penetrating deep clay belts.
P01-02-014 Quantec **Demonstration survey of the distributed acquisition method MT/IP earth imaging technology**	A prototype system will be demonstrated to show that it will quantitatively map lithology, structure, alteration, and mineralization. The data collected will be interpreted using 3D earth models with GoCAD.	The challenge is to demonstrate the technology in a variety of geological environments and over several control sites in northern Ontario. The technology is designed to detect mineralization to depths of 1000 m in areas of glacial cover. The new technology will be capable of mapping the bedrock geology.
P01-02-016a University of Ottawa **Geochemical detection of buried and disseminated palladium mineralization in northwestern Ontario**	The research will target mafic and ultramafic igneous rock complexes in the search for palladium and platinum using pathfinder elements.	A new type of platinum group metal deposit has emerged in Ontario. The challenge is to identify possible ore-bearing rocks when there is no clear geophysical signature. Commercial assaying methods are expensive with high detection limits and have limitations in targeting potential areas. The research will examine alteration, dispersion, solubility, leaching, and precipitation barriers. The result will be concepts for geochemical exploration and anomaly definition.
P01-02-018 York University **Geodata Analysis Systems (GeoDAS) for mineral exploration in Ontario**	The goal of this research is to demonstrate the GeoDAS methodology and feasibility to produce a state of the art GIS-based technology for predictive mineral potential mapping.	The generation of mineral exploration targets especially in areas of thick overburden cover has become increasingly difficult because of the highly diverse and complex data sets. GeoDAS has the capability and functionality to handle this challenge.

Table 36.1. continued

Proposal #, Name and Title	**Project Goals**	**Exploration Challenge Addressed**
P01-02-021 Quantec **Airborne hyperspectral surface mapping over exposed and covered mineral belts in Ontario**	This project will evaluate the capabilities of the hyperspectral sensor and software for detecting rock alteration that may be indicative of 'blind' ore deposits.	This project will address the need to be able to systematically and efficiently collect hpyerspectral data from an aircraft. The result being the demonstration of a new tool for geologic mapping and definition of new prospective terrain for mineral exploration.
P01-02-023 Mira Geoscience **3D Data integration methodology and tools for in-mine and near-mine exploration**	Demonstration of new 3D data interpretation method and software through case studies, using rock property modelling, and geochemical and geophysical data to maximize success in drill hole targeting.	In areas of complex geology the challenge is to integrate and interpret the wealth of data collected during exploration in and near mine sites. This new software will deliver an efficient and cost-effective means to carry out drill hole targeting, which will lead to successful mineral exploration and the discovery of new ore reserves.
P01-02-005b Gedex **Gedex AGG (airborne gravity gradiometer) system**	This project focusses on research, development and testing of system components of a prototype high-resolution gravity gradiometer.	Currently, the only available airborne gravity system does not have the sensitivity required for the majority of mineral deposits. The Gedex AGG system will provide rapid, airborne data collection that will have significantly greater sensitivity and bandwidth enabling it to find deposits that are invisible to other systems.
P02-03-025 T. C. Barrie and Associates **Geochemistry of graphitic argillites and iron formation near VMS and gold deposits**	This research project will investigate geochemical and geophysical characteristics of interflow sedimentary graphitic argillites and iron formations. The resultant signatures and mineral potential mapping will target mineral deposits under cover.	The project will provide useful databases on graphitic argillites and iron formations; it will provide new methodologies for use in geochemical exploration in areas of thick glacial cover. The alteration haloes associated with ore deposits can be recognized up to 1 km from the ore deposit using this geochemical method.
P02-03-028 JVX Ltd. **Drill hole spectral IP for poorly conducting copper/PGM mineralization in the Sudbury Basin**	This research project will demonstrate the borehole spectral IP methods to identify and model disseminated footwall sulphide and vein systems in the Sudbury Basin.	The exploration challenge is to locate and create 3D models of non-conducting sulphide zones that have the potential to carry significant platinum group metals. The outcome is the identification of diamond drill targets that are missed by conventional geophysical methods.
P02-03-031 Mira Geoscience **The downhole seismic imaging method: a new tool for deep mineral exploration**	This project will demonstrate a new tool for mineral exploration for locating ore bodies, lithological contacts and structures at a distance of up to 1 km from boreholes at depths up to 2000 m.	The downhole seismic imaging (DSI) method will transfer a technology from academic research to industry as a new tool for mineral exploration. The placement of geophones in the drill hole beneath the overburden or Paleozoic cover will reduce overburden noise, providing physical property data that will enhance the 2D and 3D subsurface images related to geological features.
P02-03-037 Camiro **Detectability of mineral deposits with potential field methods**	This project will expand the modelling criteria of ore deposit types to include data on magnetic susceptibility and comparison to density and geological data to determine ability to detect a buried deposit from the air and ground.	The exploration challenge will be to model expected responses of economic targets, understand the masking effects of the surrounding geological noise and determine the detectability versus deposit relationship of real economic ore bodies.
P02-03-034a Gedex **Onsite geochemistry for locating kimberlites and assessing diamond bearing potential in Ontario**	This project will develop and test a novel prototype pre-concentration device amenable to field conditions. These methods will be optimized for site portability without compromising analytical ability.	The challenge will be to adapt large laboratory technology to a field portable system. In order to maximize the advantages associated with this capacity, sample preparation methods must be modified to allow efficient sample throughput in the environment of a mobile lab, and to support novel analytical concepts.

Table 36.1. continued

Proposal #, Name and Title	Project Goals	Exploration Challenge Addressed
P02-03-036a Aquapath **Mineral exploration by systematic analysis of ground water upwelling in lakes and rivers**	This project will demonstrate that sampling ground water upwelling in lakes in rivers will identify the chemical signature of Archean basement terrains and zones of mineralization through which ground water has flowed.	The challenge will be to combine modelling of the geometry and geology along with the geochemistry to provide a vector towards mineralization as a cost-effective exploration tool.
P02-03-039a Bedrock Research Corp. **Development and evaluation of a tri-axial 3D magnetic survey system**	The project objectives are to evaluate newly developed C++ code and to prove the effectiveness of this methodology both with surface and subsurface data, to discern lithology, structure, geology, thermal and pressure related to remanence not discernable by conventional magnetic data modelling.	The challenges will be produce tri-axial total field maps at resolutions appropriate to mineral exploration. The effectiveness of this method needs to be proven. The uncertainty of the induced magnetism, especially in areas of structural complexity, could affect the ability to interpret the orientation of the remnant magnetism.
P02-03-038 Gamma Technologies **Development of a new helicopter-borne deep search super conducting survey system sensor technology**	The project goals are to develop a new high power airborne EM system that will be cost effective, have reduced bird wobble, with deep penetration.	The challenge is to develop a sufficiently large, yet light structure EM bird with the geometry that will provide an unprecedented 35 m spacing between the transmitter and receiver antennas. A second challenge will be to provide data that is usable by standard industry software.
P02-03-043 Bob Lo **New aircraft compensation system for magnetic terrains**	The project goal is to develop compensation software to eliminate the attitude effects of the aircraft in aeromagnetic surveys.	The challenge is to address the magnetic effect due to changing attitude of the aircraft during aeromagnetic surveys. The new compensation system will assist in the accurate interpretation of magnetic data in highly magnetic terrains.
P03-04-046 Camiro-Mira **Development of a relational physical rock properties database**	This project will capture publicly accessible relational databases and provide the rock property database on line via a standard browser. This database would be available on the Internet worldwide.	The main challenge is to source databases of physical properties of rocks from many sources and integrate the data into a standardized relational database that will be Internet accessible.
P03-04-047 Camiro-Mira **Detectability of mineral deposits with electrical resistivity and induced polarization methods**	The goal of this project is to test geophysical modes against realistic geological models of key target ore bodies and their host rock environments.	The exploration challenge is the understanding of 3-D applications of resistivity and IP to the 9 key target deposit types. Understanding how these data relate to well-constrained geology should be instructive.
P03-04-048 AUG Signals **Processing of hyperspectral data from northern Ontario using HE/LP (Hyperspectral Exploration/Lithologica l Processing) software**	This project will validate and enhance mineral signatures from hyperspectral data.	Currently, detection results from existing software tools are not reliable due to the large number of false alarms and low probably of detection by the hyperspectral sensor. The challenge will be to demonstrate that the HE/LP software will be able to provide a new tool to quantify the presence of minerals from reflectance hyperspectral data, and thereby lowering the false alarm rate.
P03-04-050 Mirarco **Quantification of the benefits of virtual reality and common earth modeling for efficient data interpretation**	The goal of this project is to integrate data from related science domains such as geology, geophysics, and geochemistry to be combined in a format that will provide a team of geoscientists with the optimum level of 3-D information management and interpretation.	The challenge will be to demonstrate that VRL technology, which is proven on the mine scale data, is applicable to regional data sets. The Lake Nipigon Region Geoscience Initiative provides a unique opportunity, in that, new geoscience data has been collected using the most up-to-date technology and should provide a good platform of data for analysis and 3-D common earth modelling through the VRL technology.

PROGRAM PERFORMANCE

The program approval rate is 50% or 25 proposals out of 50. The rejection rate is 50% or 25 of 50 proposals. Two proposals were withdrawn by the proponent.

The OMET program reports 3 performance measures: Financial Leverage; Transmission of New Knowledge to the Public; and Uptake of Technology Transfer. Table 36.2 lists the approved/funded projects as of June 30, 2004.

Table 36.2. Approved/funded OMET projects as of June 30, 2004.

Proposal		OMET Award	Researcher Cash	Researcher In-kind	Cash Leverage	Total Leverage
P01-02-001	Camiro	$ 56,100	$ 56,100	$ 0	1.0	1.0
P01-02-002	Camiro	$ 358,975	$ 262,040	$ 100,000	0.73	1.01
P01-02-003	Camiro	$ 108,825	$ 168,825	$ 120,000	1.55	2.65
P01-02-007b	Geotech	$ 356,470	$ 207,330	$ 25,000	0.58	0.65
P01-02-008a	GSC	$ 592,000	$ 166,000	$ 489,000	0.28	1.11
P01-02-011a	Ferra Dynamics	$ 74,900	$ 39,000	$ 127,750	0.52	2.23
P01-02-014	Quantec	$ 625,500	$ 190,000	$ 71,500	0.30	0.42
P01-02-016a	Ottawa Univ.	$ 168,040	$ 38,000	$ 104,000	0.20	0.85
P01-02-018	York Univ.	$ 331,500	$ 339,000	$ 175,000	1.02	1.55
P01-02-021	Quantec	$ 431,000	$ 60,000	$ 276,000	0.14	0.78
P01-02-023	Mira Geoscience	$ 529,000	$ 260,000	$ 639,000	0.49	1.70
P02-03-005b	Gedex	$ 800,000	$ 3,314,015	$ 363,000	4.41	4.60
P02-03-025	Barrie	$ 260,460	$ 7,500	$ 420,000	0.03	1.64
P02-03-028	JVX	$ 61,380	$ 38,620	$ 11,600	0.63	0.45
P02-03-031	Mira Geoscience	$ 199,120	$ 97,520	$ 91,230	0.49	0.73
P02-03-037	Camiro	$ 69,844	$ 69,844	$ 0	1.0	1.0
P02-03-034a	Gedex-Sciex	$ 83,500	$ 281,988	$ 121,000	3.38	4.83
P02-03-036a	Aquapath	$ 122,045	$ 149,165	$ 316,570	1.22	3.82
P02-03-039a	Bedrock	$ 85,263	$ 21,452	$ 161,400	0.25	2.14
P02-03-038	Gamma	$ 160,000	$ 85,000	$ 125,000	0.53	1.31
P02-03-043	B. Lo	$ 111,018	$ 37,007	$ 158,650	0.33	1.76
P03-04-046	Camiro-Mira	$ 120,000	$ 42,000	$ 40,000	0.33	0.66
P03-04-047	Camiro-Mira	$ 71,987	$ 57,305	$ 0	0.78	0.78
P03-04-048	AUG Signals	$ 125,000	$ 42,000	$ 20,000	0.34	0.50
P03-04-050	Miraroco	$ 172,000	$ 106,600	$ 175,000	0.62	1.05
TOTALS		$ 6,098,007	$ 6,369,711	$ 4,130,700	1.05	1.73

Cumulative awards to date including all fiscal years are **$6,098,007**. The researcher combined cash and in-kind support for the projects amount to **$10,527,411**. Through the OMET program an investment of **$16,625,488** will be made in new mineral exploration technologies. Ontario will be the benefactor of these new technologies and Ontario will continue to lead the way in this sector.

Performance Measure 1: Financial Leverage.
Target: \$.25 from researcher for each OMET \$1.00.
Actual: Each OMET \$1.00 levers \$1.05 researcher cash or \$1.73 researchers cash plus in-kind support. Note: This level of financial leverage demonstrates that the OMET projects are well supported by industry, universities and other governments.

Performance Measure 2: Transmission of New Knowledge to Public.
Target: 1 Transmission per project per year.
Actual: Nine projects have been competed to date: P01-02-001, P01-02-014, P01-02-021, P01-02-11a, P02-03-016a, P02-03-025, P02-03-028, P02-03-039a and P02-03-043. Projects P01-02-014 and P01-02-021 will be released before this report is published. Several projects have resulted in industry and universities taking up the new technology to do further research and use the new technology to explore for mineral deposits.

Performance Measure 3: Uptake of Technology Transfer.
Target: 1 receptor per funded project.
Actual: Both the Quantec Titan 24 and Quantec Hyperspectral projects have attracted much interest from industry and universities. There have been several surveys carried out in Ontario using the Titan 24 system following the project supported by OMET; one has yielded some interesting diamond drill results. Quantec now operates 4 systems worldwide and has completed at least 60 surveys. JVX has completed several commercial surveys since the OMET demonstration project of the new borehole spectral induced polarization (IP) instrument. The OMET office has had several inquiries as to when the results of completed projects will be published. About 20 different private companies have sponsored and co-funded the OMET funded projects. In some instances, the companies are benefiting from the testing of prototypes of the new technology. This indicates that the private sector strongly supports the technical merit and mineral exploration relevance of these research projects. Uptake of new technology is not anticipated to be an issue. The OMET program has resulted in collaboration amongst OMET participants to solve technology problems outside of the OMET program.

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Discover Abitibi Initiative

37. Discover Abitibi Greenstone Architecture Project: Overview of Results and Belt-scale Implications

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INTRODUCTION

The Discover Abitibi Initiative is funded by the private sector, the federal and provincial governments (respectively Industry Canada through FedNor and the Ontario Ministry of Northern Development and Mines through the Northern Ontario Heritage Fund). The program is designed to stimulate mineral exploration in the Ontario portion of the Abitibi greenstone belt and includes geophysical surveys of various types and two geological projects (www.discoverabitibi.com) - the "integrated geological study of the Timmins–Kirkland Lake area" and the production of three-dimensional models of 19 mineral deposits. We report on the former project here. Given the maturity of exploration in the Abitibi greenstone belt, new techniques to deal with new geological models (Ayer, Thurston et al. 2003) and the overburden cover are required. This project is designed to develop new exploration techniques for copper-zinc and nickel-copper-platinum group element (PGE) deposits through consideration of stratigraphy, volcanological facies mapping, alteration mapping, geochemistry and isotopic geochemistry and for gold deposits through consideration of stratigraphy, detailed structural mapping and transfer of mine-scale structural controls on mineralization through to the regional scale.

As this project is being done by a university-based team, Laurentian University has the potential to have the private sector portion of Discover Abitibi funding matched by a program of the Natural Sciences and Engineering Research Council of Canada (NSERC), a federal body which funds academic scientific research. If successful, this matching funding will be used to extend and expand the research begun under this project.

GOALS OF THE ARCHITECTURE PROJECT

The architecture project includes both a lode gold and a volcanogenic massive sulphide (VMS) mineralization stratigraphic component. The lode gold component is emphasizing identification of structural controls on the gold mineralization in the Timmins and Kirkland Lake camps, elucidating the role of porphyry intrusions spatially associated with gold mineralization in the Timmins camp and the relationship between gold mineralization and metamorphic patterns.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.37-1 to 37-15.

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At the scale of the Abitibi greenstone belt, this project seeks to establish the basic architecture of the major mineralized assemblages and their relationship to the greenstone belt as a whole. Through the stratigraphic projects (Hathway and Thurston 2003; Péloquin and Piercey 2003; Péloquin and Piercey 2003; Hathway, Hudak and Hamilton, this volume; Péloquin and Gibson, this volume; Piercey et al., this volume), we have revised the distribution of base metal-bearing assemblages. We have also revised knowledge of the stratigraphy of the Kidd–Munro assemblage and its relationships to the Tisdale and Blake River assemblages. This involves establishing stratigraphic sections proximal to mineralization and tracing stratigraphic and volcanological variation away from known deposits. Given the isotopic evidence for an autochthonous origin for Archean greenstone belts (Thurston 2002; Ayer et al. 2002), are the major assemblages bounded by tectonic or stratigraphic contacts? New evidence on this aspect is presented below. Does the geochemistry of felsic volcanism vary within a given assemblage? Development of detailed and regional stratigraphy provides the underpinning for understanding geological features related to mineralization such as volcanologic facies variation, structural style, alteration patterns, metamorphic patterns, etc. Therefore, in this project, we expand outward from well-characterized syngenetic deposits through detailed bedrock mapping (1:5000 to 1:20 000 scale) of key corridors within critical assemblages and integrating these data with existing regional and detailed mapping. A later component of the project will attempt to apply the detailed stratigraphic revisions on a regional scale. The stratigraphic mapping will be the first step in the volcanogenic massive sulphides-related work. Expansion of stratigraphy outward to a regional scale is proceeding as discussed below.

There are several lines of evidence for the in-place development of Abitibi greenstone belt assemblages (i.e., autochthonous development). First, the volcanic or "Keewatin" assemblages become younger with increasing distance from major batholiths, such as east of the Round Lake batholith in the Kirkland Lake area and east and north of the Kenogamissi batholith west of Timmins (Ayer et al. 2002). All but the oldest volcanic assemblage within the greenstone belt exhibit isotopic inheritance in which approximately 20% of the samples contain xenocrystic zircons similar in age to the underlying assemblages, suggesting that magma feeding the younger assemblages passed through the older stratigraphy enroute to surface. Relatively early batholiths of gneissic tonalite have a tendency to occur in regional-scale structural culminations with later granitoids both in the culminations and in the regional-scale basins (Chown, Harrap and Moukhsil 2002; Daigneault, Mueller and Chown 2004). This is consistent with the notion that the diapiric uprise of granitic batholiths was responsible for the upturning of greenstone stratigraphy in many Archean cratons (Bleeker 2002; Van Kranendonk et al. 2004).

BELT-SCALE STRATIGRAPHY: REVISIONS AND EXPLORATION IMPLICATIONS

Archean lithotectonic assemblages within a given greenstone belt are separated by age gaps of up to about 100 million years in some belts of northwestern Ontario (Williams, Stott and Thurston 1992) through to the short 3 to 10 million-year intervals in other greenstone belts such as the Abitibi or the Pilbara craton greenstone belts (Ayer et al. 2002; Hickman and Van Kranendonk 2004). Contacts between lithotectonic assemblages may be either tectonic, intrusive, or unconformities (Williams, Stott and Thurston 1992). The contacts between "Timiskaming-style" and "Keewatin-style" assemblages in the Superior Province have been considered to be subaerial unconformities marked by development of regoliths or paleosols (Jackson and Fyon 1991). However, in most Archean greenstone belts, contacts between "Keewatin" assemblages deposited in a submarine setting have more recently been assumed to be tectonic (Williams, Stott and Thurston 1992) until the very recent recognition of isotopic inheritance in Superior Province greenstone belts (Ayer et al. 2002; Thurston 2002). Submarine unconformities are characterized by the presence of manganese nodules, glauconitic sands or mass-flow deposits (Shanmugam 1988) and, in the Archean, only the latter has preservation potential.

The western part of the Abitibi greenstone belt consists of 7 "Keewatin" assemblages varying in age from approximately 2750 Ma to approximately 2700 Ma (Figure 37.1) (Ayer et al. 2002). Some of these assemblages include an uppermost unit of iron formation and/or graphitic argillite. Within the Keewatin stratigraphy of the Abitibi greenstone belt, Heather (1998) postulated that a major iron formation unit overlying the Deloro assemblage (2730 to 2725 Ma) in the main part of the belt and overlying the correlative Chester Group in the Swayze area is a regional-scale marker horizon. Heather obtained U/Pb zircon ages on units immediately underlying and overlying the major iron formation unit documenting a time gap of about 6 million years (2731±2 Ma to 2724±2 Ma) for accumulation of the iron formation. Therefore, this Deloro–Tisdale assemblage contact is considered here to be a contact of regional significance which might possibly represent an unconformity.

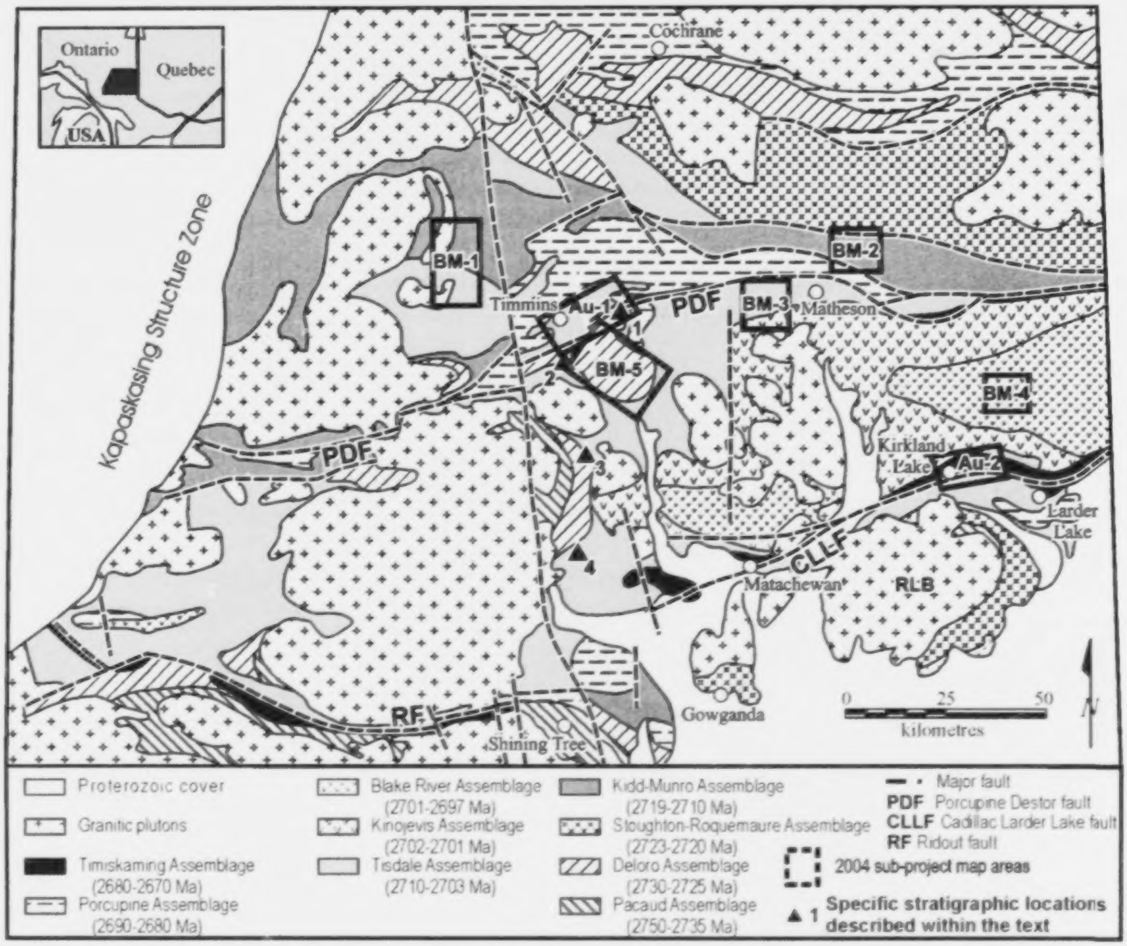
Ontario
Quebec
USA
Cochrane
Kapuskasing Structure Zone
BM-1
BM-2
BM-3
BM-4
BM-5
Au-1
Au-2
Timmins
Matheson
PDF
1
2
3
4
Kirkland Lake
Larder Lake
CLLF
Matachewan
RLB
Gowganda
Shining Tree
RF
0
25
50
kilometres
N
Proterozoic cover
Granitic plutons
Timiskaming Assemblage (2680-2670 Ma)
Porcupine Assemblage (2690-2680 Ma)
Blake River Assemblage (2701-2697 Ma)
Kinojevis Assemblage (2702-2701 Ma)
Tisdale Assemblage (2710-2703 Ma)
Kidd-Munro Assemblage (2719-2710 Ma)
Stoughton-Roquemaure Assemblage (2723-2720 Ma)
Deloro Assemblage (2730-2725 Ma)
Pacaud Assemblage (2750-2735 Ma)
Major fault
PDF Porcupine Destor fault
CLLF Cadillac Larder Lake fault
RF Ridout fault
2004 sub-project map areas
▲ 1 Specific stratigraphic locations described within the text

Figure 37.1. Assemblage map of the Ontario portion of the Abitibi greenstone belt. Assemblage boundaries are after Ayer et al., (2002). The boxes provide locations for the individual subprojects, and the triangles are locations for stratigraphic interpretations, both of which are described in the text.

Keewatin Unconformities in the Abitibi Greenstone Belt

Accordingly, the iron formation forming the upper part of the Deloro stratigraphy in the Timmins area and south of Timmins was examined in several locations shown on Figure 37.1. In Whitney Township, adjacent to the Pamour pit haul road, the iron formation at the top of the Deloro assemblage consists of banded oxide-facies iron formation intercalated with metre-scale beds of arkosic conglomerate, and metre-scale units of iron formation conglomerate (*see* Figure 37.1, location #1). On the power line in Deloro Township (*see* Figure 37.1, location #2), Deloro assemblage basalts are overlain by an iron formation unit succeeded by rocks alternatively considered either Tisdale assemblage or Krist formation felsic volcanic rocks. The iron formation is a finely laminated banded iron formation (Photo 37.1) succeeded by iron formation conglomerate containing abundant arkose and chert clasts (Photo 37.2). Some clasts of iron formation contain tabular chert clasts indicating that there have been multiple episodes of iron formation sedimentation followed by cannibalization of the early formed iron formation units.

Location #3 on Figure 37.1 indicates a representative section of the Deloro–Tisdale assemblage contact on the power line in northern English Township. Figure 37.2 is a schematic section of the Deloro–Tisdale assemblage contact in that location. At that location, from the base upward, a 3 m thickness of banded lean iron formation is succeeded by about 60 m thickness of heterolithic, unbedded, ungraded felsic pyroclastic breccia, a 5 m thickness of iron-formation conglomerate, 2 to 3 m of wackes in erosional contact with about a 60 m thickness of homolithic rhyolitic pyroclastic breccia. The felsic volcanic units, given their unbedded, non-graded nature are considered mass-flow deposits. The contact between the chert fragment-bearing wackes and the upper pyroclastic breccia unit is an erosional surface transecting the wacke unit. In summary, at each of the Deloro–Tisdale assemblage contacts shown on Figure 37.1, the "iron formation" actually consists of conventional banded iron formation, and/or iron formation conglomerate or other units deposited by mass-flow processes. This association of mass-flow units at the assemblage contacts is here interpreted to indicate that the Deloro–Tisdale assemblage contact is most likely submarine unconformity. In addition, the Tisdale assemblage in Hutt Township (*see* Figure 37.1, location #4) displays heterolithic felsic volcanic debris flows and arkoses intercalated with finely laminated chert, oxide and sulphides facies iron formation. This intercalation of mass-flow units and iron formation would suggest that this contact whether it is an internal contact within the Tisdale assemblage or the upper contact of the Tisdale assemblage may also represent an unconformity.

Muskasenda Gabbro and Stratigraphic Models

The gabbro body centred on Muskasenda Lake is a sill-like melanocratic gabbro with lesser anorthositic gabbro, quartz gabbro and pyroxenite, which extends through Bartlett, English and Beemer townships south of Timmins (Pyke 1978). It surrounds an enclave of felsic metavolcanic rocks with a Deloro assemblage age of 2728±2 Ma (Ayer, Trowell et al. 2003), establishing that the gabbro is younger. Easterly striking gabbro and quartz gabbro dikes, perpendicular to stratigraphy, extend through the overlying Deloro assemblage felsic metavolcanic rocks in Bartlett and English townships are possibly a set of basaltic feeder dikes to Tisdale assemblage mafic volcanic flows in Douglas and Zavitz townships. This dike relationship provides field evidence for the autochthonous origin of the basaltic rocks fed by these dikes. Therefore, a sample of quartz gabbro dike in Bartlett Township has been obtained for U/Pb zircon geochronology. This radiometric age will clarify the age of the dikes and thus provide another line of evidence for autochthonous origin of the Keewatin assemblages of the Abitibi greenstone belt.

The suggestion here of the unconformable contacts between Keewatin assemblages, particularly the Deloro–Tisdale assemblage contact, suggests that it will in future be possible to establish stratigraphic correlation on a stratigraphic basis to complement the isotopically based revisions to Abitibi greenstone belt stratigraphy suggested by Ayer et al. (2002).

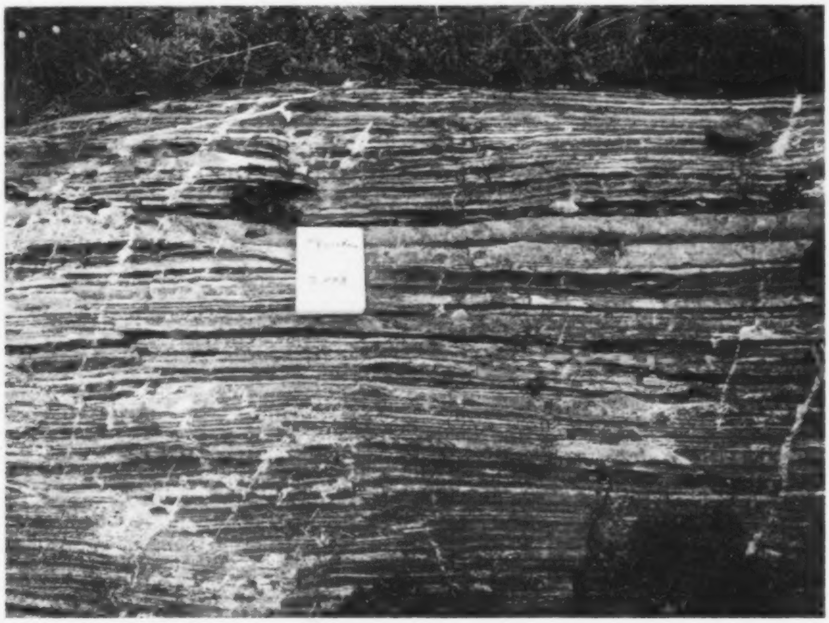

Photo 37.1. Classical banded iron formation at the Deloro–Tisdale assemblage contact in Deloro Township.

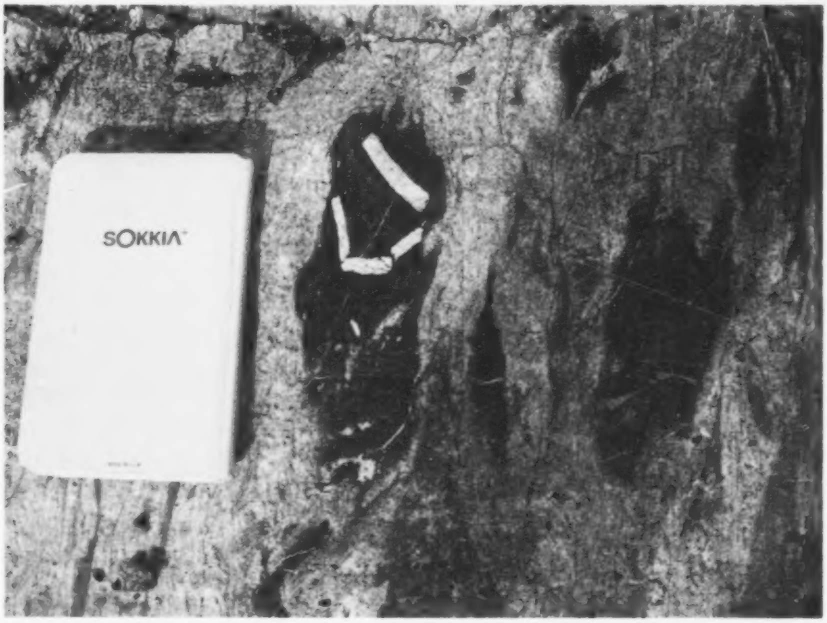

Photo 37.2. Clast in iron formation conglomerate containing chocolate tablet-style fractured chert fragment in an iron formation clast. Location as in Photo 37.1.

VOLCANOGENIC MASSIVE SULPHIDE MINERALIZATION STRATIGRAPHIC PROJECTS

The subprojects summarized in this section are designed to improve understanding of the stratigraphy, volcanic facies, alteration and structure of the parts of the Tisdale and Kidd–Munro assemblages most likely to host mineralization. The area for year two of work on the Tisdale assemblage (*see* Figure 37.1, BM-1) (Hathway, Hudak and Hamilton, this volume) was selected because of uncertainty about the extent of Tisdale assemblage rocks north and west of last year's area (Hathway and Thurston 2003), their degree of correlation with the mineralization at Kam-Kotia, Jameland and Halfmoon Lake and the relationship between Tisdale assemblage rocks and Kidd–Munro assemblage rocks to the north in Macdiarmid and Loveland townships. In the central part of the Abitibi greenstone

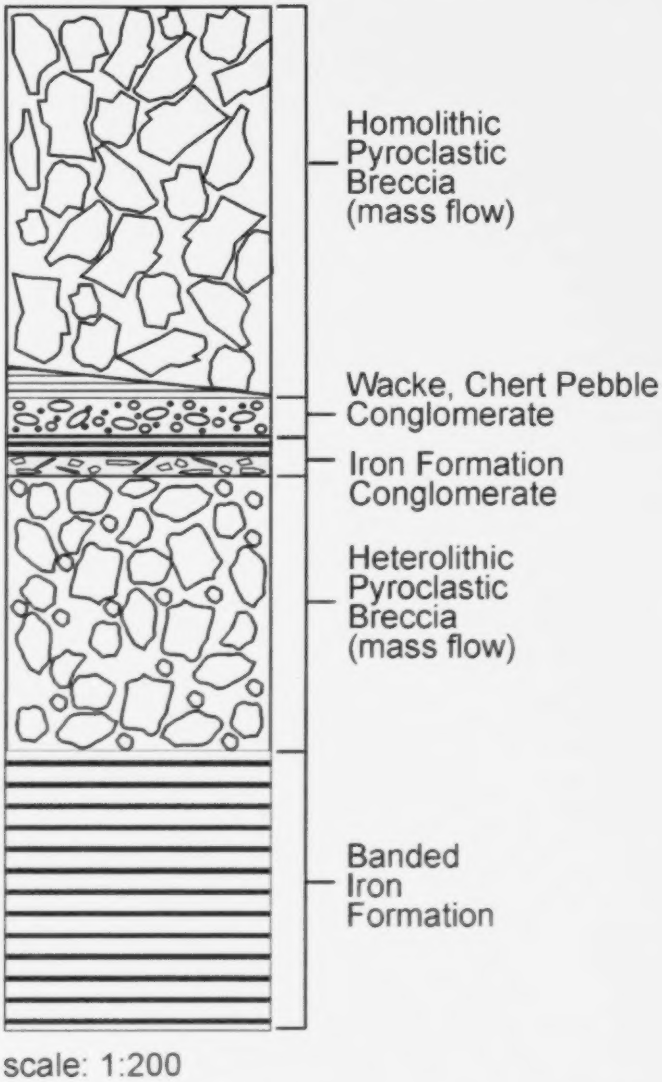
Homolithic Pyroclastic Breccia (mass flow)
Wacke, Chert Pebble Conglomerate
Iron Formation Conglomerate
Heterolithic Pyroclastic Breccia (mass flow)
Banded Iron Formation
scale: 1:200

Figure 37.2. Schematic stratigraphic section of the Deloro–Tisdale assemblage contact in northern English township. Note the erosional contact between the wacke, chert pebble conglomerate unit and the homolithic pyroclastic breccia.

belt, the first year's work involved characterization of the Blake River assemblage (Péloquin and Piercey 2003) and in this, the second year, the project moves on to characterize the stratigraphy of the Kidd–Munro assemblage toward the eastern end of its extent in Ontario (*see* Figure 37.1, BM-2) and the relationship between the Tisdale assemblage and the overlying Kinojevis assemblage (*see* Figure 37.1, BM-3) (Péloquin and Gibson, this volume). A MSc project examining the controls on VMS mineralization at the Genex Mine (Hocker, Thurston and Gibson, this volume) continued field work this year.

Kamiskotia Area Subprojects

Hathway, Hudak and Hamilton (this volume) have developed a comprehensive stratigraphy for the Tisdale assemblage extending from Turnbull Township northwest to the Halfmoon Lake area (*see* Figure 37.1, BM-1). The stratigraphy mapped on the eastern limb of an anticline (Hathway and Thurston 2003) in 2003 extends northward through the Jameland and Kam-Kotia deposits. They identify 2 key marker horizons: the Steep Lake tuff with distinctive dark chloritic lapilli and the Ski Hill tuff of rhyolitic composition and containing sparse dark lapilli. This stratigraphy and stratigraphic facing direction permitted identification of a regional-scale syncline lying east of the aforementioned anticline. In general, the stratigraphic succession mapped this year is traceable in detail between the Kam-Kotia deposit and the Steep Lake region. The stratigraphic column constructed places the Genex mineralization below the mineralized horizon at Kam-Kotia and Jameland. New U/Pb zircon ages place the stratigraphy in this region at 2698 to 2701 Ma. These geochronologic results requires either extension of the age of the Tisdale assemblage or equating these units with the Blake River assemblage. The later option is favoured because the bimodal tholeiitic nature of basalts and rhyolites in the Kamiskotia area is more characteristic of the Blake River than the upper Tisdale assemblages (Ayer et al 2002). Detailed mapping of the volcanic rocks associated with the mineralization at the Kam-Kotia deposit has provided a revised stratigraphic setting for the mineralization.

The Genex deposit study (Hocker, Thurston and Gibson, this volume) has identified 2 generations of intrusions associated with the deposit: one clearly synvolcanic, one slightly later. These pre-metamorphic sills have in large part utilized synvolcanic faults to access the upper part of the stratigraphy. Thus, whereas Genex was a relatively small deposit with a short mining history, the presence of synvolcanic structures and magmatism indicates that the deposit fulfils many of the criteria for a favourable VMS environment. As well, the stratigraphic position of the host rocks at Genex is now clear in a regional sense (Hocker, Thurston and Gibson, this volume; Hathway, Hudak and Hamilton, this volume). The Genex deposit stratigraphy is toward the base of the assemblage and is overlain by a unit of clastic metasedimentary rocks forming a stratigraphic break followed by the stratigraphy hosting the Kam-Kotia and Jameland deposits.

Assemblages and Mineralization Environments, Northeast Abitibi Greenstone Belt

Péloquin and Gibson (this volume) have documented the stratigraphy of the Kidd–Munro assemblage in the Munro township area (*see* Figure 37.1, BM-2) . The stratigraphy south of the Munro fault zone consists of unusual spherulitic or variolitic felsic and mafic volcanic units forming a northeast-younging succession. Between the Munro fault and the Centre Hill fault, the units exposed consist of massive and pillowed flows mafic and rare ultramafic flows within a central syncline. North of the Centre Hill fault in tholeiitic and komatiitic rocks of the Kidd–Munro assemblage are the Potter and Potterdoal VMS deposits. The deposits lie in a sequence of basal komatiites succeeded by tholeiites and komatiites.

The mineralization is hosted in the mafic sequences, in tholeiitic spatter deposits and along an interflow contact between tholeiitic flows, respectively. The project also examined the contact between the Tisdale and Kinojevis assemblages in Currie township (*see* Figure 37.1, BM-3). The contact is at the so-called "Marker Horizon", a unit of argillites, felsic and intermediate tuffs and wackes similar to the clastic unit overlying the Genex deposit stratigraphic units (S. Hocker, Laurentian University, personal communication, 2004). The Marker Horizon is also the locus of locally intense sericitization silicification and carbonatization. The Marker Horizon hosts gold and base metal mineralization, which may be syngenetic (Ayer, Thurston et al. 2003).

INTRUSION SUBPROJECT

Piercey et al. (this volume) have revised their interpretation of stratigraphy of the Blake River assemblage units (*see* Figure 37.1, BM-4) relative to their report of 2003 (Péloquin and Piercey 2003). Many of the units formerly considered andesitic flows are now considered pyroclastic rocks. The Blake River assemblage rocks are cut by the Clifford Stock, largely tonalite to granodiorite. There is a local contact metamorphic aureole surrounding the stock. VMS-style alteration, consisting of amygdule filling of chlorite-quartz-epidote-pyrite assemblages, represents semi-conformable style alteration. The VMS alteration is overprinted by porphyry-style Cu-Au-Mo alteration associated with breccia-pipe-style occurrences (e.g., Brett–Trethway [also known as Croxall] prospect). Preliminary geochronologic results indicate that the age of the Clifford stock is approximately 2687 Ma, similar to the ages of other magmatic units cutting Blake River stratigraphy in Québec. Felsic dikes cutting the metavolcanic rocks have an age of 2688 Ma, equivalent in age to the Clifford stock. The ages of the Blake River assemblage rocks are approximately 2695 Ma, an age which overlaps existing ages for the Blake River Group in Ontario and Québec (Piercey et al., this volume) strengthening a correlation of stratigraphy in this project area with the Noranda region of Québec.

NICKEL-COPPER-PLATINUM GROUP ELEMENT SUBPROJECT

An affiliated project, by the Ontario Geological Survey (OGS), has been designed to complement the Discover Abitibi Greenstone Architecture Project. It is focussed on Ni-Cu-PGE mineralization in the Shaw Dome area south of Timmins, in the vicinity of the Langmuir, Hart, McWatters, and Redstone deposits (*see* Figure 37.1, BM-5) (*see* Houlé and Guilmette, this volume). Ni-Cu-(PGE) sulphide mineralization associated with komatiitic rocks (komatiites and komatiitic basalts) in Archean and Proterozoic greenstone belts are an important part of the broader category of magmatic Ni-Cu-PGE mineralization. The goals of this project are three-fold: 1) to evaluate the subvolcanic-volcanic architecture of the ultramafic rocks of the Shaw Dome; 2) to evaluate the Ni-Cu-PGE mineral potential of the komatiitic rocks; and 3) to better understand the stratigraphic and structural configuration of the ultramafic rocks in the context of the Shaw Dome. Geophysical and diamond-drill hole data are being used to aid in the extrapolation of geological contacts across the many large areas obscured by overburden.

The Discover Abitibi Greenstone Architecture Project is collaborating with this OGS project by contributing funds towards geochronological determinations of critical lithogical units (*see* Houlé and Guilmette, this volume) and three-dimensional inversion models of magnetic and gravity data (*see* "Geophysics" below), in order to better understand the stratigraphic location of, and the structural controls on, the stratabound Ni-Cu-PGE deposits in the margin of the Shaw Dome.

GOLD SUBPROJECTS

The goal of the gold subprojects is to identify and characterize the key geological parameters controlling the formation and distribution of gold deposits at the district scale in order to help design exploration strategies. The key parameters include outcrop-scale structures, lithologic units, intrusions and alteration facies that control the distribution of the mineralization and/or host the mineralization. The project will also better delineate the stratigraphy of units hosting gold mineralization, and the Porcupine and Timiskaming unconformities and their roles in the localization of gold mineralization. At a regional scale, we address important knowledge gaps concerning the tectonic evolution of the southern Abitibi greenstone belt, focussing on the main fault zones that disrupt the stratigraphy and localize gold deposits. Mapping and sampling has been carried out in regions that straddle the Porcupine–Destor deformation zone (PDDZ) (Bateman et al., this volume) and the Larder–Cadillac deformation zone (LCDZ) (Ispolatov, Lafrance and Dubé, this volume) by including the highly deformed fault zone rocks and the less deformed rocks proximal to the fault zones. In this way, we will be able to define the strain gradient and identify preserved structures that may be related to an early stage of rifting (Ayer et al. 2002) that could have accompanied early generations of gold mineralization. Detailed kinematic and structural mapping are required to establish the structural evolution of the fault zones, including successive reactivation events. The role of the major fault zones in disrupting stratigraphy, creating permeable zones for gold mineralization and the relative and absolute age constraints of the gold mineralizing event are key parameters for our investigation as are the spatial and structural relationships between the PDDZ and the Dome fault; and between the LCDZ and the Kirkland Lake "Main Break". The close spatial association between gold mineralization and porphyry intrusions along the PDDZ is also being investigated for the possible explanations for this linkage and for criteria to aid in the exploration for this type of mineralization (MacDonald, Piercey and Hamilton, this volume). Finally, the role of metamorphism in localizing gold mineralization, and exploration tools for using metamorphic facies in exploring for gold, are addressed (Thompson, this volume).

Timmins Camp Subproject

The Timmins area gold subproject (*see* Figure 37.1, Au-1) integrates deposit-scale knowledge of the gold deposits into a camp-scale stratigraphic, structural and alteration framework. This work is being accomplished by outcrop and pit mapping, diamond-drill core examination, detailed structural observations and lithogeochemical and geochronological sampling of critical units. The subproject began in the eastern part of the camp in Hoyle and Whitney townships (Bateman, Ayer and Dubé 2003). This summer's work was focussed in Tisdale and Deloro townships and along the Porcupine–Destor deformation zone. Six generations of deformation with associated folding, faulting and tectonic fabric development have been documented (Bateman et al., this volume). D1 and D2 are pre-Timiskaming assemblage in timing, are of regional extent with major folding and faulting associated with them, but have only weak foliations developed in the camp. D3 and D4 are post-Timiskaming assemblage and deformation associated with these events are most obvious in a broad corridor proximal to the Porcupine–Destor deformation zone where they have well-developed foliations. The Porcupine–Destor deformation zone has undergone both subhorizontal and subvertical displacements related to these early deformation events. It has early, generally south-dipping ductile deformation overprinted by late brittle faulting associated with the north-dipping Dome fault. Gold mineralization occurs mainly within the Tisdale assemblage basalts and, to a lesser extent, within the Timiskaming assemblage sedimentary rocks. Although there is evidence for an early gold mineralization event, it appears to be minor. The majority of the gold is associated with the D3 and D4 events, whereas D5 and D6 are late crenulation events which have locally overprinted and/or remobilized the gold mineralization. D1 to D4, and the gold mineralization events have been assigned absolute timing using the U/Pb and Re/Os isotopic systems, both of which show the main gold mineralization event followed closely after deposition of the Timiskaming assemblage at approximately 2670 Ma (Ayer, Barr et al. 2003; Bateman et al., this volume).

Dinel and Fowler (this volume) report on the results of an affiliated PhD project at the University of Ottawa. This project is focussed on better understanding the role of stratigraphy, lithofacies, alteration and structure in controlling gold mineralization at the Hoyle Pond Mine. On the basis of very detailed lithogeochemical traverses, this work has shown that the metavolcanic units hosting the deposit are a homoclinal panel of the Tisdale assemblage, bound to the north and south by younger Porcupine assemblage metasedimentary rocks. This evidence supports the presence of early thrust faulting (D1 or D2) at the northern and possibly the southern contact between the assemblages, similar to the relationships described by Bateman et al. (this volume) in northern Tisdale Township.

Kirkland Lake Camp Subproject

The Kirkland Lake area gold subproject (*see* Figure 37.1, Au-2) integrates deposit-scale knowledge of the Kirkland Lake area into a camp-scale geological framework using similar methodologies to the Timmins subproject. Work began in the eastern part of the camp in Gauthier Township (Ispolatov, Lafrance and Dubé 2003). This summer's work was focussed in Teck Township where most of the known gold mineralization is associated with the Main Break or the Kirkland Lake fault located about 2 km north of the Larder–Cadillac deformation zone (Ispolatov, Lafrance and Dubé, this volume). Five generations of structures have been identified in the camp. S1 is pre-Timiskaming assemblage and is only found in the Tisdale assemblage rocks, whereas S2, the earliest deformation fabric present in the Timiskaming assemblage rocks is mainly developed in proximity to the Larder–Cadillac deformation zone. S3 is expressed as a north-trending (350 to 005°) crenulation cleavage dipping moderately to steeply (50 to 70°) to the east and axial planar to east-southeast plunging symmetric and Z-asymmetric folds. S4 is the most common deformation fabric in the Timiskaming assemblage rocks. It generally strikes 040 to 055° and dips steeply to the southeast or northwest. Along the Larder–Cadillac deformation zone, S4 is a spaced crenulation cleavage overprinting S2. S4 is weakly developed in the centre of the map area, but it increases in intensity in metapyroclastic and metasedimentary rocks of the Timiskaming assemblage north of the Kirkland Lake fault, where it forms a discrete spaced cleavage, which is generally oriented counterclockwise to bedding and axial planar to Z-shaped folds. S5 is a late crenulation cleavage that was identified in the Gauthier Township area. It trends at 130 to 170° and dips 30 to 80°W. No map-scale structure is associated with the development of S5.

More than one gold mineralization episode is also suggested by the studies in the Kirkland Lake camp where early gold mineralization is found in both the Timiskaming and Tisdale assemblages and is interpreted to be coeval with S2 in proximity to the Larder–Cadillac and Upper Canada deformation zones at the Anoki, McBean, and Upper Canada mines (Ispolatov, Lafrance and Dubé 2003). In Teck Township, the most significant gold mineralization occurs in the Timiskaming assemblage rocks cut by the Kirkland Lake fault, a brittle to brittle-ductile fault striking approximately 065° and dipping steeply to the south. Gold mineralization generally occurs along this fault and closely related subsidiary faults that was likely synchronous with the D4 deformational event (Ispolatov, Lafrance and Dubé, this volume). Uranium-lead (U/Pb) zircon and Re/Os molybdenite geochronology is being undertaken to better constrain the absolute timing of these events.

Porphyry Subproject

This subproject is focussed on the role and characteristics of "porphyry" intrusions spatially associated with gold deposits along the Porcupine–Destor fault. MacDonald and Piercey (2003) subdivided the Timmins area porphyry bodies into 2 trends: the Vedron–Paymaster–Dome (central trend) and the Hollinger–McIntyre–Coniaurium (northern trend). This year, the work has expanded to examine porphyry bodies in Bristol Township (western trend), in Shaw Township (southern trend) and east of

Timmins (eastern trend) (MacDonald, Piercey and Hamilton, this volume). They describe contact relations of the porphyries and country rock and a variable alteration mineralogy. Most gold mineralization is associated with intense sericite and moderate ankerite alteration.

Observations from this research suggest that gold mineralization is most strongly correlated with the porphyry bodies in the Timmins camp that show intense sericite alteration coupled with moderate ankerite alteration. The presence of multiple porphyry bodies in intensely deformed areas of the belt also seems to be important in the development of the Timmins gold deposits (e.g., Hollinger–McIntyre and Dome). Even though most of the porphyry bodies examined show some gold enrichment, recent radiometric determinations of the McIntyre and Dome gold mineralization events suggests at least a 15 million-year span between porphyry emplacement and gold mineralization and, therefore, there is no genetic link between porphyry intrusions and gold mineralization (MacDonald, Piercey and Hamilton, this volume; Ayer, Barr et al. 2003). Two possibilities remain for the strong spatial relationship between porphyry intrusions and gold mineralization: 1) that gold mineralization developed during regional deformation because of the competency difference between the porphyries and the surrounding mafic volcanic rocks; and/or 2) that the porphyry intrusions and gold-bearing fluids utilized the same long-lived structures at different times.

Metamorphic Subproject

This subproject is designed to upgrade the metamorphic framework for gold exploration at a regional scale in the Timmins–Kirkland Lake area of the Abitibi greenstone belt. Metamorphic data and concepts used to explain the origin and evolution of metamorphic rocks contribute to the reconstruction of the geological setting of gold deposits and provide key constraints on the nature, timing, duration and distribution of gold mineralization and related hydrothermal alteration. In this way, metamorphic tools advance knowledge of known deposits and help to define new exploration targets. Thompson (this volume) identifies areas of anomalously low or anomalously high metamorphic grade as well as areas with closely spaced metamorphic isograds, all signs of anomalous fluid flow possibly related to mineralization.

In addition to looking at metamorphic conditions at a regional scale in the Timmins to Kirkland Lake region, the subproject also focussed on the more detailed metamorphic conditions in the vicinity of the Dome Mine in Timmins, where thin sections were examined from units at the surface and to depths of 2000 m. This preliminary study (Thompson, this volume) indicates that at the Dome and Paymaster mines, the high metamorphic-grade anomalies found at surface narrow with depth. This geometry is consistent with metamorphic zoning in the third dimension that is as irregular as it is on the surface. At least to depths of 2000 m, the increase in grade does not outline a simple thermal dome. This more detailed work confirms the spatial relation between the Dome Mine and an upper greenschist zone metamorphic anomaly and supports the working hypothesis that metamorphic anomalies are favourable prospects for gold mineralization.

GEOPHYSICS

Geophysical interpretation is a crucial component of the Greenstone Architecture Project due to the thick overburden and scattered nature of bedrock exposures in the Abitibi greenstone belt. All government airborne geophysical data, magnetic electromagnetic and gravity data have been made available to the project as an in-kind donation by the Ontario Geological Survey. New Discover Abitibi Initiative geophysical surveys have also been used to aid in interpretation. A number of the subproject areas are transected by two-dimensional reflection seismic surveys conducted last summer and funded by the Discover Abitibi Initiative. The seismic data is scheduled for release in 2004 and will aid the Architecture subprojects in interpretations of the distribution of lithological units and structural features at depth.

The geophysical consultant to the project is providing customized interpretations and plots such as three-dimensional inversions of magnetic and gravity data in each of the subproject map areas. These three-dimensional models are being used to better interpret the distribution of lithological units and structural features both at the surface and at depth, and will be used to help construct more realistic cross-sections. An example of the type of magnetic data product being developed is shown for the Shaw Dome area in Figures 37.3 and 37.4. These data assisted in developing the extensively revised interpretation of the extent of individual assemblages in the Shaw Dome area. All the models for the subproject areas will also be released in digital form as an OGS Miscellaneous Release—Data in 2005.

RECOMMENDATIONS

The Discover Abitibi Greenstone Architecture subprojects all have an economic focus and, thus, the following reports have criteria and/or suggestions that will be of assistance to explorationists. However, the implications of this information in the mapping-based projects is also applicable to the regional scale; thus, favourable assemblages, units and/or structures should also be examined for their economic potential beyond the borders of these subprojects. An example of this is the widespread iron formations of the Abitibi greenstone belt. This rock type is the host unit for a significant number of the gold mines in the Yilgarn craton in Australia and at the Musselwhite Mine in the Superior Province of northwestern Ontario. Although, to date, only relatively minor amounts of gold have been extracted from deposits of this type in Abitibi greenstone belt (e.g., the Carshaw Mine in the Shaw Dome, *see* Houlé and Guilmette, this volume), it is felt that the potential of these chemically favourable units to host large gold deposits have been largely overlooked in the Abitibi greenstone belt. Recent work by International KRL Resources Corp. at the Golden Sylvia occurrence in MacMurchy Township in the Shining Tree area, have shown Deloro assemblage iron formation units in this area (Photos 37.3 and 37.4) have significant amounts of gold mineralization with relatively low but very consistent grades over broad areas (up to 500 m in strike length, *see* www.krl.net). This mineralization may represent material suitable for open pit development, similar to many of the iron formation hosted gold mines in the Yilgarn craton. It is as yet uncertain what the structural control on this mineralization may have been, but this mineralization demonstrates that the combination of chemically favourable units and/or structures needs to be examined more closely in a large number of as yet under-explored areas of the Abitibi greenstone belt.

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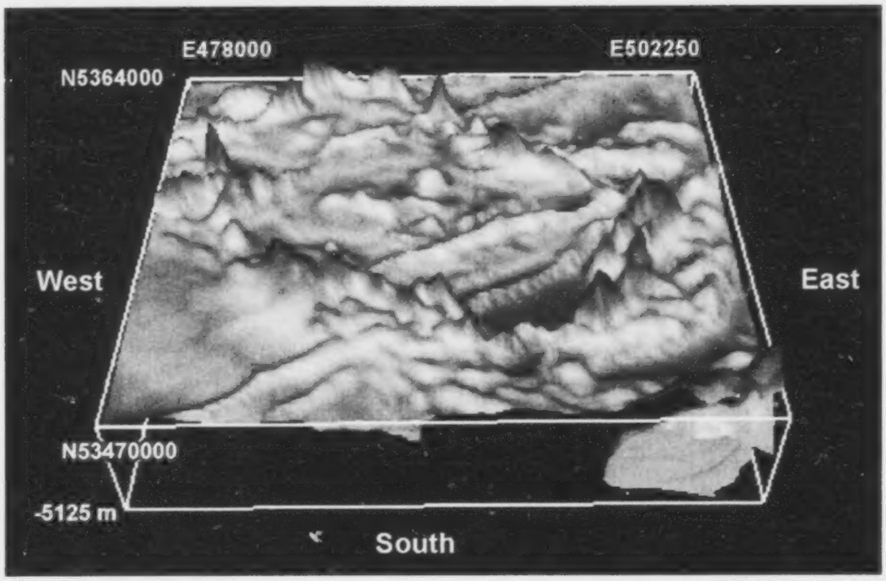
E478000
E502250
N5364000
West
East
N53470000
-5125 m
South

Figure 37.3. Amplitude enhanced magnetics of the Shaw Dome area viewed from the south at 45° above the horizon. The magnetics were also inverted (inversion shells just seen under the south edge) from the International Geomagnetic Reference Field removed magnetic field.

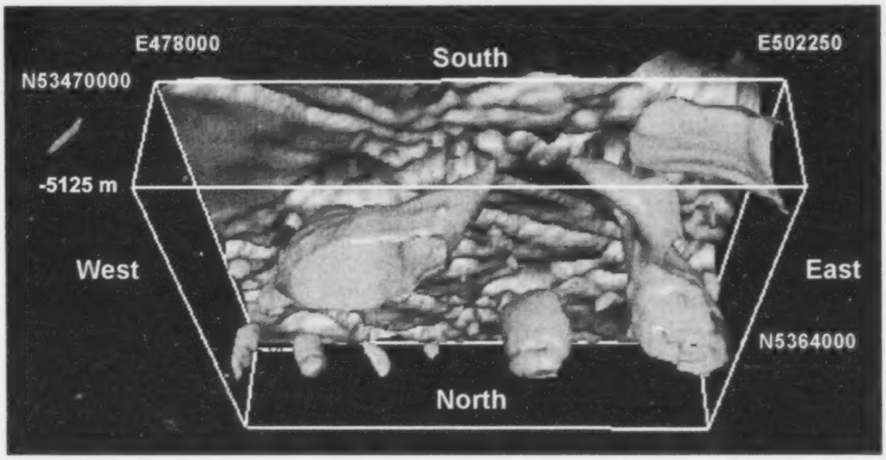
E478000
South
E502250
N53470000
-5125 m
West
East
N5364000
North

Figure 37.4. Shaw Dome area as above, viewed from the south at 45° below the ground surface. Sample magnetic inversion shells at 50 000 SI 10^{-6} units and the amplitude enhanced magnetics. T he magnetic data were inverted using 250 metre horizontal and 125 metre vertical cells. The elevated magnetic patterns correspond with thick iron formation and ultramafic units located around the margin of the structure.

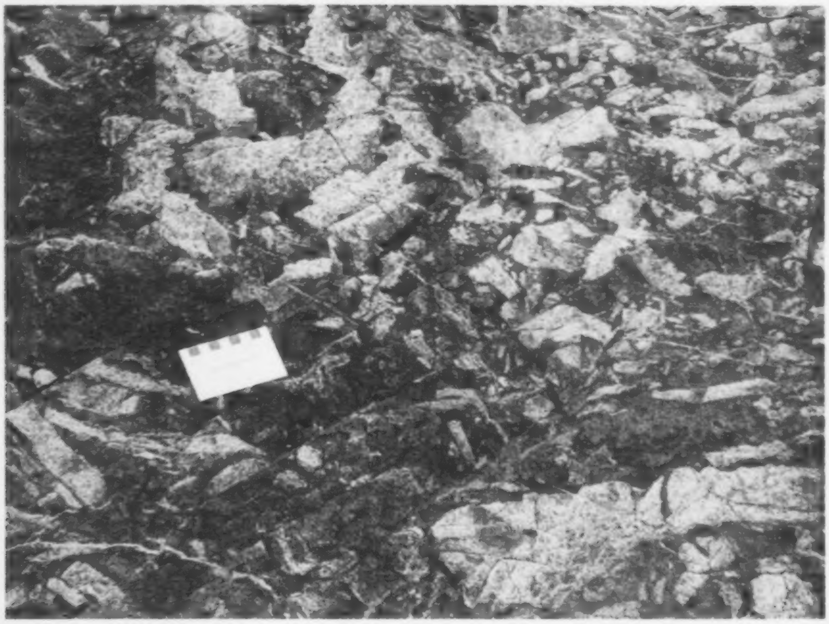

Photo 37.3. Brecciated chert clasts in iron formation at the Golden Sylvia occurrence in MacMurchy Township.

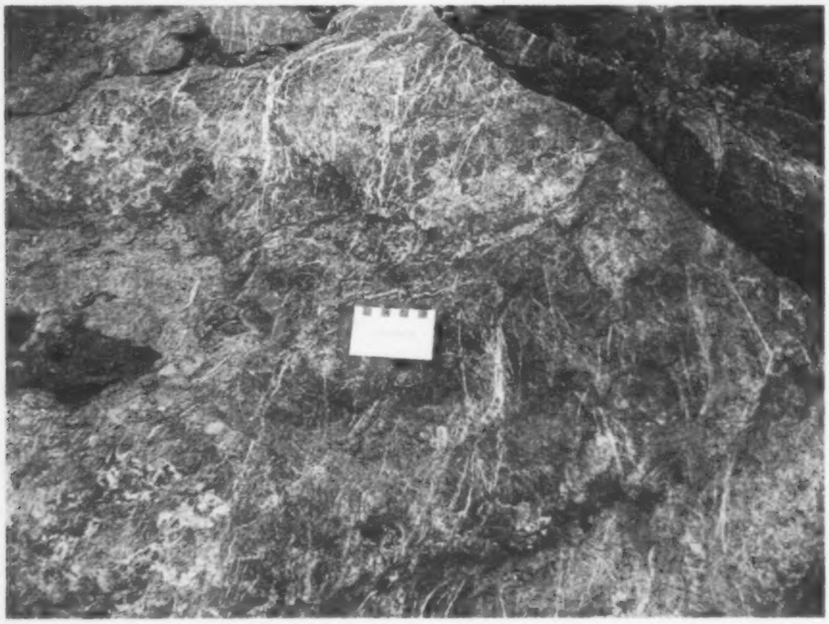

Photo 37.4. Chert-rich iron formation at the Golden Sylvia occurrence in MacMurchy Township. Note multiple generations of cross-cutting quartz veinlets, which typically carry fine gold.

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38. Discover Abitibi. Base Metal Subproject 1. Geological Setting of Volcanogenic Massive Sulphide Mineralization in the Kamiskotia Area

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INTRODUCTION

The main goal of this subproject is to understand the stratigraphy, volcanic facies, alteration and structural style associated with copper-zinc volcanogenic massive sulphide (VMS) mineralization in the Kamiskotia area (Abitibi greenstone belt, Timmins region). During the 2004 field season, regional-scale mapping (by B. Hathway) covered the northern of the two selected bedrock mapping corridors, including parts of Godfrey, Robb, Jamieson, Loveland, Macdiarmid and Thorburn townships (Figure 38.1). This area is contiguous with the southern corridor mapped in 2003 (Hathway and Thurston 2003). Deposit-scale work within the regional mapping area (by G. Hudak), focussed on the Kam-Kotia VMS deposit, site of the largest past-producing mine in the area.

There are 2 published age determinations for the volcanic succession in the study area. An age of 2705±2 Ma from the rhyolites in Godfrey Township (Barrie and Davis 1990), places them in the Tisdale assemblage (2703 to 2710 Ma: Ayer et al. 2002). The second age, of 2719.5±1.7 Ma from southern Thorburn Township (Ayer et al. 2002), indicates that rocks in the northern part of the study area form part of the older Kidd–Munro assemblage. Here, we present and discuss new U/Pb zircon ages (by M.A. Hamilton) for samples collected in 2003 from the immediate vicinity of 3 of the VMS deposits.

RESULTS

Regional Mapping

The 2004 regional mapping area can be divided into a southern (Robb, Jamieson and northern Godfrey townships) and a northern area (Loveland, Macdiarmid and Thorburn townships), separated by a corridor with no outcrop and little available drill-core data along the Kamiskotia River.

ROBB, JAMIESON AND NORTHERN GODFREY TOWNSHIPS

The volcanic rocks in this area lie to the east and northeast of the Kamiskotia Gabbroic Complex (Barrie 1992, 2000), and host past-producing VMS deposits at the Kam-Kotia, Jameland and Canadian Jamieson mines, and significant base-metal prospects at Halfmoon Lake and Steep Lake (*see* Figure 38.1). Although this succession has been thought of as a north- and east-facing monocline (e.g.. Barrie and Pattison 1999), southwest-facing sections noted by Middleton (1973a, 1973b) in southern Jamieson township have implied a more complex structure.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.38-1 to 38-8.

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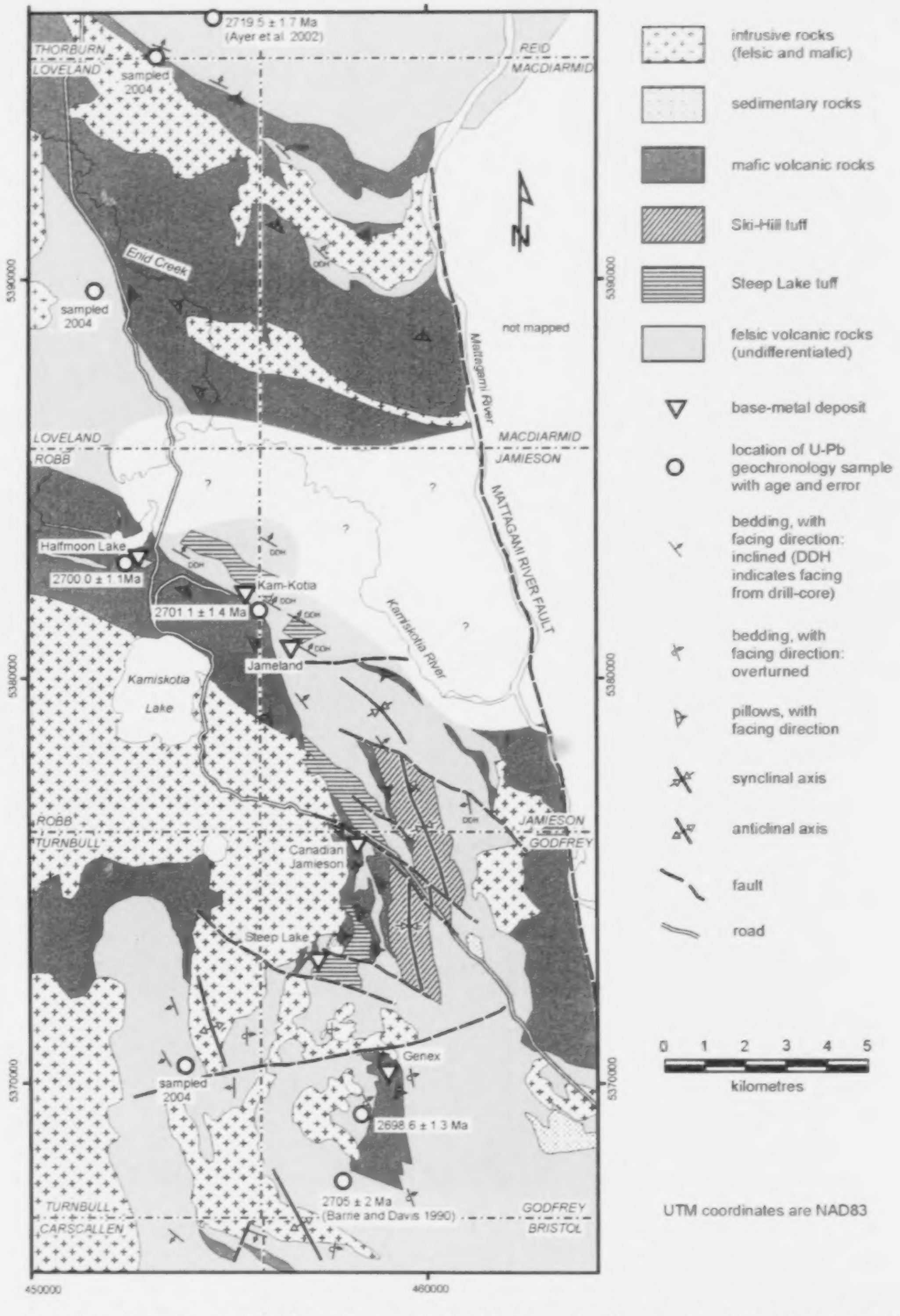
2719.5 ± 1.7 Ma
(Ayer et al. 2002)
THORBURN
LOVELAND
sampled
2004
REID
MACDIARMID
Enid Creek
sampled
2004
5390000
not mapped
Mattagami River
LOVELAND
ROBB
MACDIARMID
JAMIESON
MATTAGAMI RIVER FAULT
Halfmoon Lake
2700.0 ± 1.1Ma
Kam-Kotia
2701.1 ± 1.4 Ma
DDH
Jameland
Kamiskotia River
Kamiskotia
Lake
5380000
ROBB
TURNBULL
JAMIESON
GODFREY
Canadian
Jamieson
Steep Lake
Genex
sampled
2004
5370000
2698.6 ± 1.3 Ma
2705 ± 2 Ma
(Barrie and Davis 1990)
TURNBULL
CARSCALLEN
GODFREY
BRISTOL
450000
460000
intrusive rocks
(felsic and mafic)
sedimentary rocks
mafic volcanic rocks
Ski-Hill tuff
Steep Lake tuff
felsic volcanic rocks
(undifferentiated)
base-metal deposit
location of U-Pb
geochronology sample
with age and error
bedding, with
facing direction:
inclined (DDH
indicates facing
from drill-core)
bedding, with
facing direction:
overturned
pillows, with
facing direction
synclinal axis
anticlinal axis
fault
road
0 1 2 3 4 5
kilometres
UTM coordinates are NAD83

Figure 38.1. Preliminary geological sketch map of the Kamiskotia area, based on data from this study and from Hogg (1955a, 1955b) and Middleton (1973b, 1974b, 1976).

The 2004 mapping shows that from Jameland Mine south to Steep Lake, the volcanic rocks form a north-northwest-trending syncline, cut by a series of northwest-trending cross faults with apparent dextral offset (*see* Figure 38.1). The western limb of the syncline forms the eastern limb of the anticline mapped to the southwest in 2003 (southern Godfrey and eastern Turnbull townships: Hathway and Thurston 2003). The eastern limb of the syncline is less well exposed, with exposure fading out towards the Mattagami River. To the north and west of Jameland Mine, facing directions from surface outcrop and drill core are uniformly to the northeast, and the syncline axis may lie farther north and east, perhaps along the Kamiskotia River. Within the area there are 2 key, mappable marker intervals, informally named here:

1. the *Steep Lake tuff* crops out extensively to the south and east of Steep Lake and to the northeast of Canadian Jamieson. It is only seen on the better exposed, western limb of the syncline, and cannot be traced south of the northwest-trending fault 1 km south of Steep Lake. It also occurs in the immediate hanging wall of the Kam-Kotia deposit, both in small surface outcrops and more extensively in drill core. This distinct, but texturally variable package of tuff and lapilli tuff is up to 800 m thick in the area south of Steep Lake. The most characteristic facies consists of dark, chloritic lapilli set in a paler, more or less felsic matrix, with a distinctive "spherulitic" texture, although in much of the package the matrix has a more intermediate composition and is strongly chloritic. These rocks were described from the Kam-Kotia area by Barrie and Pattison (*see also* 1999, Figure 6: "intermediate lapilli ash tuff") who suggested that they represent mixed-magma eruptions. Coarse-grained, possibly cognate, gabbroic and felsic (quartz-feldspar crystal aggregate) inclusions are relatively abundant at some levels, supporting this conclusion.

2. the *Ski-Hill tuff* forms the core of the north-northwest-trending syncline, and appears to be the youngest exposed part of the Kamiskotia volcanic succession. It lies 250 to 500 m stratigraphically above the Steep Lake tuff (intervening rocks include basalt pillow lava, massive rhyolite and felsic tuff), but unlike that unit, it could not be identified north of the northwest-trending fault 2 km north of Canadian Jamieson Mine. The tuff has a basal division up to 100 m thick rich in quartz and feldspar crystals (exposed on both limbs of the syncline). The upper part (approximately 400 m thick) consists of fine, uniformly felsic tuff (generally not "spherulitic" as in the Steep Lake tuff) which may contain sparse, dark lapilli (usually <1 cm). Lapilli are larger (long axes up to 20 cm) and more abundant in the lower part of the upper division, and this part of the unit is locally stratified or bedded. The Ski-Hill tuff has been previously mapped as massive rhyolite (Hogg 1955a, 1955b; Middleton 1976).

LOVELAND, MACDIARMID AND THORBURN TOWNSHIPS

Observed facing directions in these townships are uniformly to the northeast (*see* Figure 38.1). From southwest to northeast, the volcanic succession consists of

1. massive, typically flow-banded and quartz-feldspar phyric rhyolite, with some felsic volcaniclastic rocks noted in drill-core

2. pillowed and massive basaltic lava, with two felsic volcaniclastic intervals (drill-core only, no surface outcrop) towards the top of the lava pile in the east

3. felsic volcaniclastic rocks with minor graphitic argillite intervals. These extend up section into Thorburn Township, where U/Pb geochronology indicates that they form part of the Kidd–Munro assemblage (Ayer et al. 2002).

The succession is cut by numerous mafic sills, and in the northwest by a number of felsic intrusions (quartz-feldspar porphyry and coarser grained granitoid rocks). Only the major intrusive bodies are shown on Figure 38.1.

Kam-Kotia Mine Area

From mid-June through mid-August 2004, 1:5000 to 1:1000 surface geological mapping was completed to better understand the volcanic stratigraphy, alteration mineralogy, and structural deformation present in the immediate area of the former Kam-Kotia orebodies (Figure 38.2). These deposits produced 583 600 tonnes (6 436 000 tons) of massive sulphide ore with an average grade of 1.11% Cu and 1.21% Zn (Barrie and Pattison 1999).

Geological mapping indicates the presence of a steeply northeast-dipping, northeast-younging succession of mafic and felsic lavas and volcaniclastic strata, chemical metasedimentary rocks (chert exhalites and massive sulphide horizons), and mafic intrusive rocks. From the base of the stratigraphic sequence, the geological section in the immediate vicinity of the Kam-Kotia mine is as follows:

1. basalt pillow lavas, pillow lobes, and associated hyaloclastite up to 155 m thick
2. interbedded, commonly fining-upward sequences comprising thinly bedded to very thickly bedded, commonly vaguely normally graded rhyolite tuff breccias, lapilli tuffs and tuffs which vary from 60 to 80 m thick and locally contain chert horizons up to 2 m thick
3. a second horizon of basalt pillow lavas and associated hyaloclastite that is up to 95 m thick
4. coherent spherulitic rhyolite with localized autoclastic and hyaloclastite breccias and tuff breccias varying from 4 to 25 m thick which are locally replaced by semi-massive to massive pyrite
5. coherent spherulitic rhyolite 8 to 16 m thick
6. a second horizon of coherent spherulitic rhyolite with localized autoclastic and hyaloclastite breccias and tuff breccias which are 8 to 25 m thick and are locally replaced by semi-massive to massive pyrite
7. a second horizon of coherent, spherulitic rhyolite ranging from 8 to 33 m thick
8. intermediate lapilli tuffs and tuffs varying from 13 to 67 m thick
9. a third horizon of basalt pillow lavas and associated hyaloclastite ranging from 16 to 25 m thick
10. a rhyolite tuff horizon that is at least 60 m thick

Two distinctive intrusive units occur in the vicinity of the Kam-Kotia Mine. Fine-grained diabase dikes and fine- to medium-grained diabasic to gabbroic sills and dikes occur in the immediate footwall and hanging wall to the largest of the Kam-Kotia orebodies. These intrusive rocks have sharp, fine-grained (apparently chilled) contacts. The footwall sill is up to 90 m thick and is characterized by a distinctly amygdaloidal zone (up to 20% 1 mm to 1 cm quartz amygdules) which is up to 4 m thick, occurs 1 to 3 m south of its uppermost contact, and can be traced along strike for at least 450 m. Fine-grained mafic dikes (described by Barrie and Pattison (1999) as pyroxenite dikes) occur locally on outcrops rimming the Kam-Kotia open pit and apparently crosscut the massive sulphide mineralization.

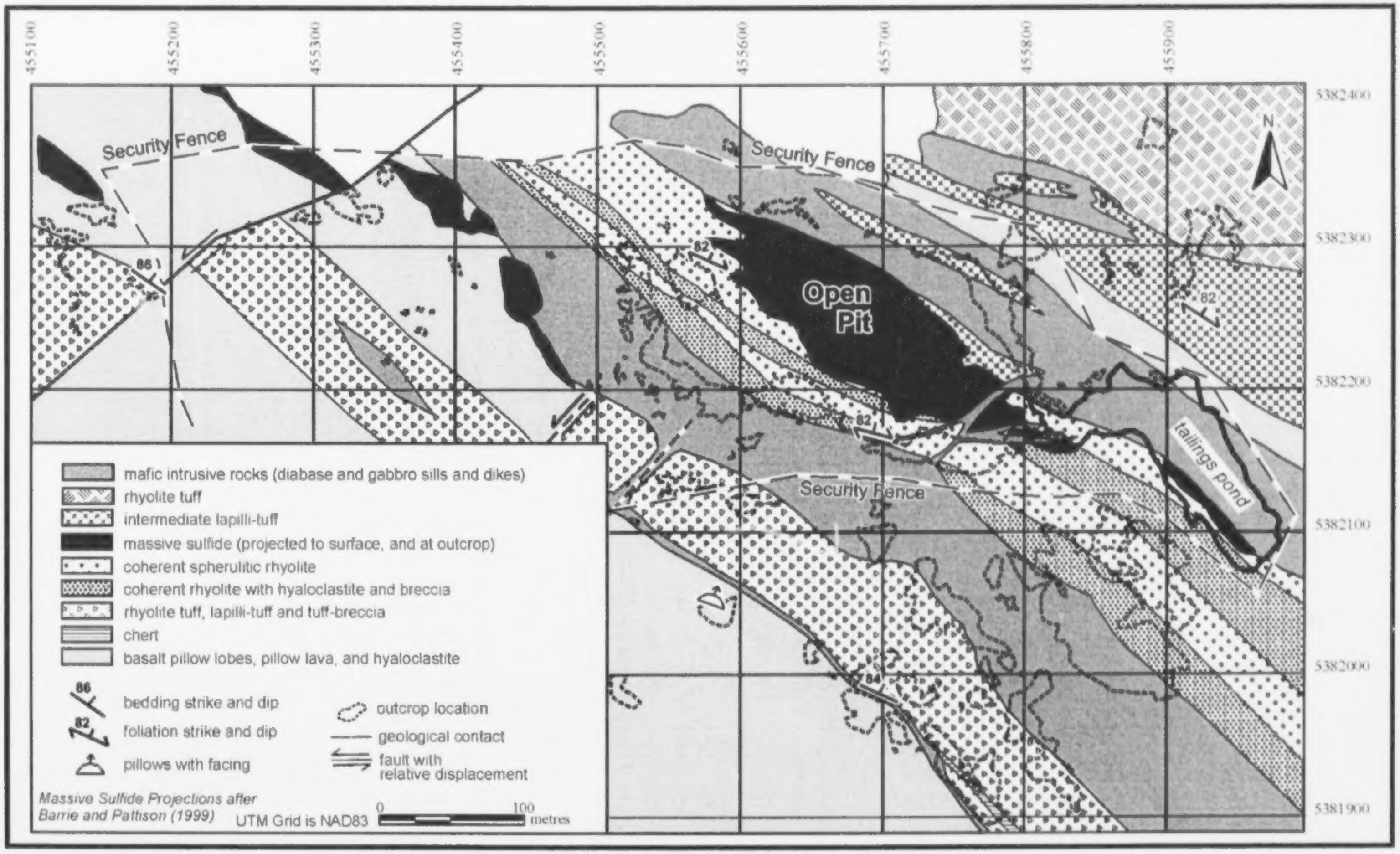
455100
455200
455300
455400
455500
455600
455700
455800
455900
5382400
5382300
5382200
5382100
5382000
5381900
N
Security Fence
Security Fence
Security Fence
Open Pit
tailings pond
86
82
82
82
82
84
mafic intrusive rocks (diabase and gabbro sills and dikes)
rhyolite tuff
intermediate lapilli-tuff
massive sulfide (projected to surface, and at outcrop)
coherent spherulitic rhyolite
coherent rhyolite with hyaloclastite and breccia
rhyolite tuff, lapilli-tuff and tuff-breccia
chert
basalt pillow lobes, pillow lava, and hyaloclastite
bedding strike and dip
foliation strike and dip
pillows with facing
outcrop location
geological contact
fault with relative displacement
Massive Sulfide Projections after Barrie and Pattison (1999)
UTM Grid is NAD83
0
100
metres

Figure 38.2. Detailed surface geological map of the Kam Kotia Mine area.

Based on vertical projections of the former massive sulphide deposits (Barrie and Pattison 1999), the main Kam-Kotia orebody appears to have been hosted within rhyolite lava flows and associated rhyolite breccias and hyaloclastites. The common relationship between semi-massive and massive sulphide mineralization and rhyolite hyaloclastite suggests that the Kam-Kotia deposits may have largely formed as synvolcanic replacement-type (Doyle and Allen 2003) massive sulphide deposits. Up-dip ore projections, as well as descriptions of the ore geology by Somerville (1967) suggest that ore lenses to the west of the main ore zone were hosted in mafic volcanic and volcaniclastic strata.

Quartz, sericite and chlorite are the most abundant alteration minerals present within the volcanic and volcaniclastic strata proximal to the Kam-Kotia mineralization. Quartz commonly occurs as 1 to 3 mm haloes along the rims of angular, chloritized rhyolite hyaloclastite lapilli west and south of the open pit that contained the main Kam-Kotia orebody. Chlorite locally makes up over 70% of chloritized felsic and mafic units within a few hundred metres of the massive sulphide mineralization, and is particularly strong within 50 m of the former deposit on the western wall of the open pit. Strong (up to 75%) sericite alteration commonly occurs within and immediately adjacent to massive sulphide mineralization that crops out along the southeastern part of the Kam-Kotia open pit.

A west-northwest striking (280 to 320°), steeply northeast-dipping (71 to 90°), foliation is commonly observed in the area and, along with the steeply dipping strata (75 to 90°), indicates the presence of an antiformal axis to the west of the Kam-Kotia Mine area. Foliation intensity is variable, with phyllosilicate-altered volcaniclastic strata commonly exhibiting more developed, more tightly spaced cleavage than less altered or coherent volcanic rocks. Locally, boudinaged fragments of lapilli tuff are tightly z-folded about east-northeast-trending axes northwest of the open pit.

U/Pb Ages

The 3 new U/Pb zircon ages are detailed below (sample locations are shown in Figure 38.1):

- *Sample 03-BHA-0345*: felsic lapilli-tuff from outcrop 800 m south-southwest of Genex Mine (UTM NAD 83: 458483E, 5369414N). Age: 2698.6±1.3 Ma.
- *Sample 03-BHA-0382*: rhyolite from diamond drill-core R44-14, 97 to 100.5 m (Falconbridge Halfmoon Project), 200 m south of Halfmoon Lake (UTM NAD 83: 452482E, 5382803N). Age: 2700±1.1 Ma.
- *Sample 03-BHA-0384*: felsic lapilli tuff from outcrop 500 m southeast of Kam-Kotia Mine (UTM NAD 83: 455853E, 5381788N). Age: 2701.1±1.4 Ma.

DISCUSSION

Regional Mapping and U/Pb Ages

Regional mapping in 2003 and 2004 has provided a new structural and stratigraphic framework for the VMS deposits in the Kamiskotia area, indicating that they lie on the shared east-facing limb of a north-northwest trending anticline–syncline pair.

The Steep Lake tuff, the lower of the two marker horizons identified in 2004, lies at or close to the top of the base-metal deposits at Steep Lake, Canadian Jamieson, Jameland and Kam-Kotia, indicating that they are at approximately the same stratigraphic level (the Halfmoon Lake deposit appears to lie somewhat lower in the stratigraphy). This volcaniclastic package seems likely to represent a major eruptive phase that may have brought VMS mineralization to a close in the area. Neither the Steep Lake nor the younger Ski-Hill tuff were identified in the Genex Mine area, and precise correlation of that deposit with those farther north is difficult. However, the rocks there and in the core of the anticline to the west (Hathway and Thurston 2003) are likely to be older than the Steep Lake tuff. They are dominated by intercalated rhyolite and felsic lapilli-tuff, and lack the thick packages dominated by fine-grained felsic tuff seen in the younger strata to the northeast, which seem to mark a shift towards more explosive felsic volcanism in the upper part of the Kamiskotia volcanic succession.

The 3 new U/Pb ages are within error of each other, and indicate a similar timing for VMS mineralization at Genex, Kam-Kotia and Halfmoon Lake. Ayer et al. (2002) included these rocks in the Tisdale assemblage on the basis of the Barrie and Davis (1990) age of 2705±2 Ma. However, the new ages are at variance with that earlier determination. They indicate that this volcanic succession is slightly younger than the youngest previously known Tisdale assemblage rocks (2710 to 2703 Ma), and coeval with the younger Blake River assemblage (2701 to 2697 Ma: Ayer et al. 2002).

The age of 2719.5±1.7 Ma from the upper part of the succession in the northern part of the study area, and the new, younger ages from Kam-Kotia and Halfmoon Lake imply some kind of structural discordance in the Kamiskotia River area. Drill-core compilation and geophysical interpretation for this area is currently in progress. Further geochronological samples were collected from Thorburn and Loveland townships (*see* Figure 38.1 for locations) in order to confirm, and establish the extent of, Kidd–Munro assemblage rocks in the area.

Kam-Kotia Mine

Detailed mapping has identified the various volcanic facies and intrusive rocks that are exposed in the immediate vicinity of the Kam-Kotia massive sulphide orebodies. In summary, the sequence comprises a bimodal sequence of supracrustal Neoarchean coherent and volcaniclastic mafic and felsic rocks and chemical sedimentary rocks, along with mafic intrusive rocks. Pillowed basalts, mafic and felsic hyaloclastite deposits, chert horizons, massive sulphide mineralization, and hydrothermal alteration assemblages consistent with those found in modern seafloor hydrothermal systems indicate that the volcanic section in this region was originally deposited in a subaqueous environment. Although the presence of amygdule-rich coherent facies has been used by previous authors (Barrie and Pattison 1999) to suggest formation in a shallow submarine environment, the depth of water at which the massive sulphide deposits and associated volcanic and volcaniclastic strata were deposited remains poorly constrained.

Petrographic studies, geochemical evaluations, structural analysis, and review of historical mine documents will allow the preliminary interpretations from this study to be further constrained.

EXPLORATION SUGGESTIONS

Recognition of large-scale folds in the Kamiskotia volcanic succession raises the possibility of repetition of the stratigraphic interval hosting the known VMS deposits. Areas suggested for further investigation on this basis would be the eastern limb of the syncline, towards the Mattagami River in Godfrey and Jamieson townships, as well as the western limb of the anticline in Turnbull Township. Surface exposure and drill-core data are sparse in both areas.

ACKNOWLEDGMENTS

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39. Discover Abitibi. Base Metal Subproject 2. The Role of Early Subvolcanic Intrusive Rocks in Development of Volcanogenic Massive Sulphide Mineralization in the Genex Mine Area, Kamiskotia Area

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INTRODUCTION

The Base Metals Subproject of the Discover Abitibi Initiative is a group of projects aimed at addressing the volcanic facies, lithology, structure and alteration of the Kamiskotia and Blake River areas to establish stratigraphic controls, identify horizons containing base metal mineralization, and define key marker horizons within the Abitibi greenstone belt. As part of the Base Metals Subproject, geologic mapping and diamond drill core logging of the stratigraphy, deformation, and alteration in the Genex Mine area, of the Tisdale assemblage, has been completed over the past 2 summers in order to better define the stratigraphy and to determine the controls on volcanogenic massive sulphide (VMS) mineralization in the Genex area.

Work in the Genex Mine area during the 2003 field season revealed that the volcanic stratigraphy is considerably more deformed and complicated than initially shown by previous mapping (Hocker et al. 2003). During the 2004 field season, work focussed on better defining the volcanic stratigraphy around the Genex Mine, with particular attention paid to two previously poorly understood intrusive bodies in the area.

This report summarizes our newest ideas and interpretations and some details differ from previous interpretations; this publication supersedes all previous reports and interpretations.

VOLCANIC STRATIGRAPHY

Mapping at scales of 1:1000, 1:100 and 1:50 during the 2003 and 2004 field seasons shows that the area surrounding the Genex deposit is a bimodal volcanic succession with dominantly mafic metavolcanic pillowed and massive flows, associated felsic tuffs and flows, mafic tuffs, mafic and intermediate intrusions (Figure 39.1). All volcaniclastic rocks are described using Fisher's (1966) non-genetic classification for volcaniclastic rocks. A succession of graded sedimentary rocks is present on the eastern side of the Genex area. The area is also cut by several Proterozoic, Matachewan diabase dikes (Middleton 1975; Legault 1985). Pillow topping indicators, as well as bedding and grading in the felsic units indicate that stratigraphy throughout the field area is uniformly near vertical to overturned and east-younging.

Extrusive mafic metavolcanic units consist of pillowed and massive flows as well as minor mafic tuffs. Within the pillowed units, there is great variability in pillow size, pillow hyaloclastite thickness, amygdule and vesicle percentage and degree of alteration. Significant variations in pillow size,

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Ontario Geological Survey, Open File Report 6145, p.39-1 to 39-9.

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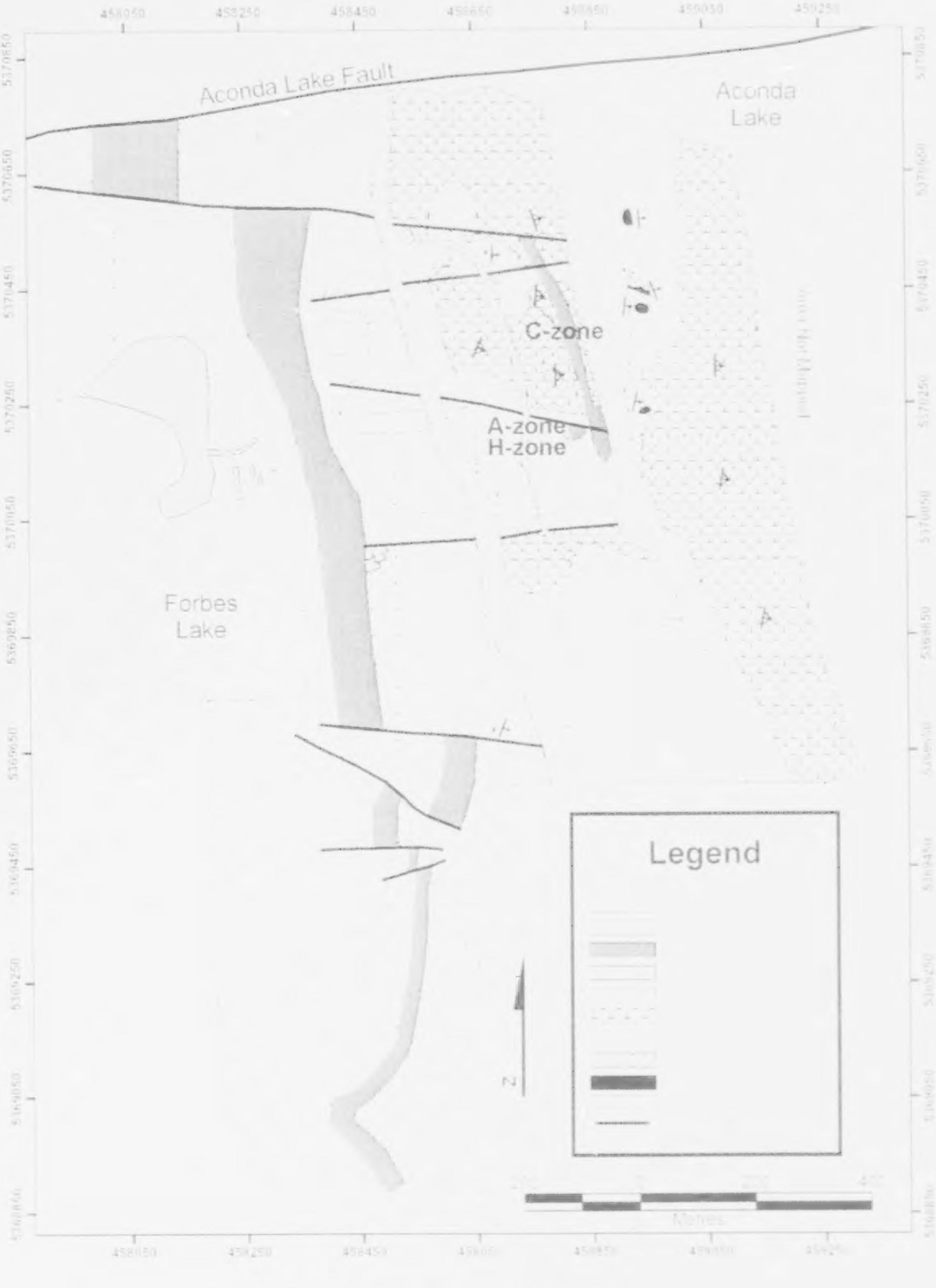
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Aconda Lake Fault
Aconda Lake
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H-zone
Forbes Lake
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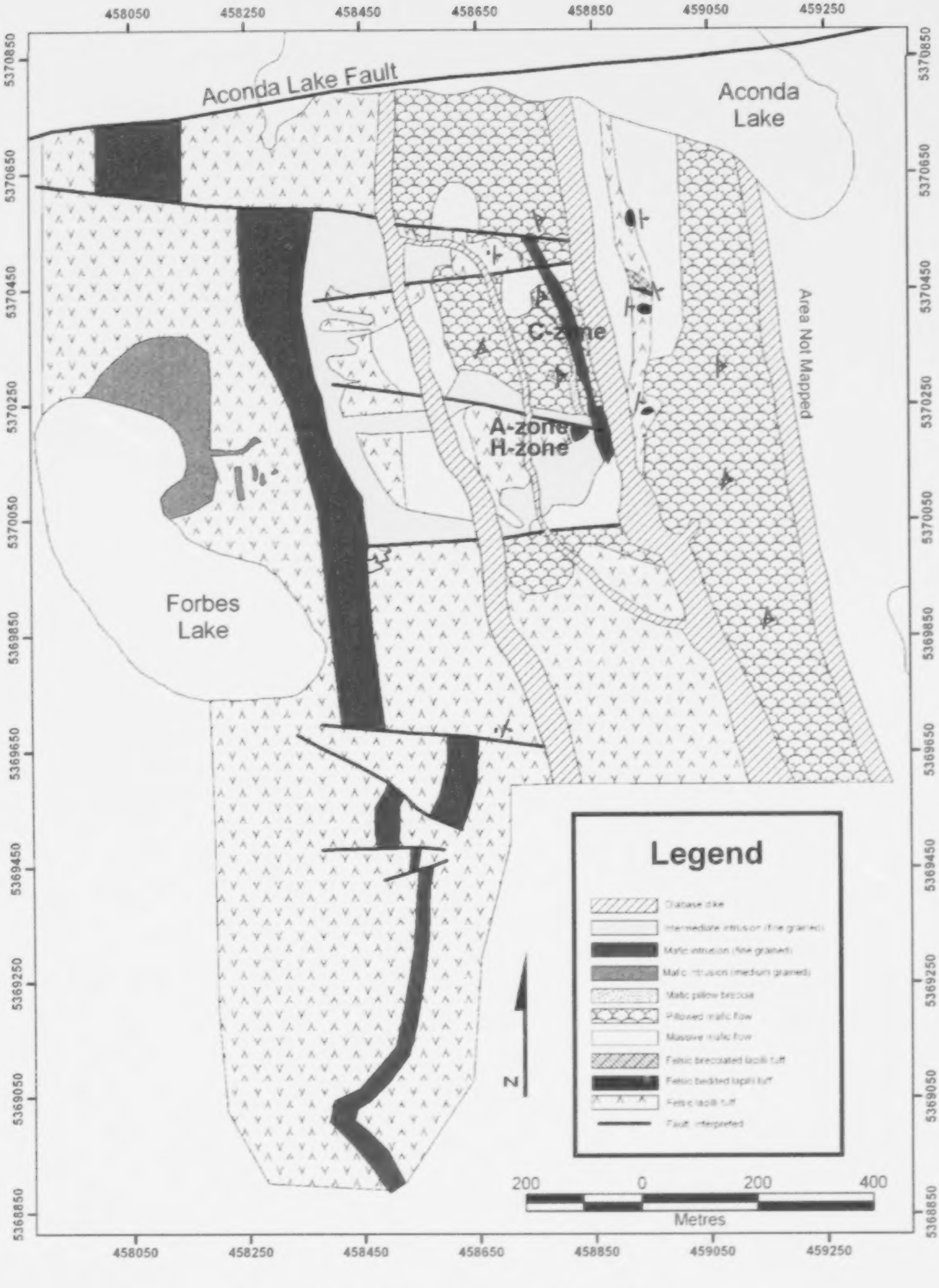
Figure 39.1 [illegible]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Aconda Lake Fault
Aconda Lake
Area Not Mapped
C-zone
A-zone
H-zone
Forbes Lake
N
Legend
Diabase dike
Intermediate intrusion (fine grained)
Mafic intrusion (fine grained)
Mafic intrusion (medium grained)
Mafic pillow breccia
Pillowed mafic flow
Massive mafic flow
Felsic brecciated lapilli tuff
Felsic bedded lapilli tuff
Felsic lapilli tuff
Fault, interpreted
200
0
200
400
Metres

Figure 39.1. Simplified geology map of the Genex Mine area.

morphology, strike, and flow direction documented in pillows in the immediate footwall of the deposit indicate downslope movement of the flow from a paleotopographic high, with the crest located at or near the C-zone orebody. Small pillow breccia units and massive basal flow units are also found associated with the pillow flows. Mafic tuffs are found in proximity to pillowed and massive flows, and range from fine-grained tuffs to lapilli tuffs. The proximity of massive mafic units to the faults in the Genex area, as well as their morphology (*see* Figure 39.1) suggests that they may represent feeders for the pillowed flows.

Field work during 2004 has recognized 2 distinct intrusions that cut the metavolcanic stratigraphy, representing two magmatic events. The oldest intrusion is a north-trending mafic synvolcanic intrusion that cuts across the base of the mine stratigraphy and a separate body that cuts the hanging wall, stratigraphically above, and in contact with, the deposit. Amoeboid-shaped mafic dikes are present in the footwall, and contain incorporated fragments of felsic lapilli tuff. The later intrusion is a north-trending sill, intermediate in composition, that cuts the footwall of the stratigraphy and also the mafic intrusion. Numerous dikes stem from the main intrusive body, and commonly contain xenoliths of felsic breccia.

Felsic metavolcanic rocks in the area surrounding the Genex deposit range from felsic tuffs to felsic breccias. Normally graded lapilli tuff to bedded tuff sequences are found throughout the area. Tuff breccias are much more common at the base of the mine stratigraphy, and contain lapilli- to block-size fragments that are commonly of the same composition as their matrix. The tuff breccias locally exhibit broken and contorted flow banding, locally contain flow-banded fragments and, *in situ*, are brecciated. In one locality in the Genex area, an amygdaloidal felsic tuff is present with up to 15%, 1 to 5 mm quartz-filled amygdules in close proximity to a crosscutting dike of synvolcanic intrusion.

Sedimentary rocks on the eastern edge of the Genex Mine area are visible only in drill core, and occur in the portion of Figure 39.1 marked "area not mapped". The hundreds of metres thick sequence of sedimentary and volcaniclastic rocks is composed of metres-thick units grading from felsic heterolithic lapilli or block tuffs to tuffs to black, finely laminated, locally pyritic mudstones. There is abundant evidence of soft-sediment deformation, graded beds, and cross-bedding throughout the succession.

DEFORMATION

Relative to the other VMS deposits in the Kamiskotia area, the Genex deposit is undeformed (Hathway, Hudak and Hamilton, this volume; Hocker et al. 2003). The strata are uniformly east facing, without evidence of folding. There are, however, numerous east-trending faults that cut the area, defining several down-dropped blocks with obvious displacement (based on field relationships) indicating an extensional tectonic regime. Faulting in the area is believed to be synvolcanic to just after waning volcanism, as evidenced by the utilization of faults as conduits for the intermediate intrusion. Numerous east-trending shear zones are also present throughout the area.

MAFIC INTRUSION

The oldest intrusion in the Genex area is a massive synvolcanic mafic intrusion, manifested as a north-trending sill that obliquely cuts the mine stratigraphy in both the footwall of the deposit and in the immediate hanging wall, in contact with the mineralization.

Within the Genex area, the intrusion is a gabbro with grain size ranging from fine to medium grained in outcrop, and coarse grained in drill core. In both outcrop and drill core, the intrusion has a blue grey colour when fresh, and a red brown colour when weathered, with locally abundant fracture-controlled pyrite mineralization. Polygonal and columnar joints are locally visible in the thicker sections of the intrusion. In both drill core and outcrop, the intrusion contains 1 to 30% quartz amygdules along contacts and becomes nonamygdaloidal toward the centre of the intrusion.

The lower contact of the intrusion is locally pillowed, and locally peperitic (observed only in drill core). The peperite and pillowed base indicates that the intrusion is a high level, synvolcanic intrusion emplaced relatively close to the seafloor (tens to hundreds of metres below the seafloor) into relatively unconsolidated, water-saturated felsic tuffs (Cas and Wright 1988). The upper contact is rarely observed in either drill core or in outcrop as it is cut by a later intrusion, but where observed it is irregular but sharp with numerous amoeboid dikes stemming from the main sill. The dikes locally contain blocks of felsic tuff, and there is evidence that the felsic rocks are being incorporated within the intrusion while they are still unconsolidated (Photo 39.1).

Evidence of the intrusion's synvolcanic nature is displayed by the presence of amoeboid dikes stemming from the main intrusion, a peperitic base, evidence of incorporation of felsic material, and the fact that the intrusion is cut and displaced by the numerous faults that run through the Genex area.

Petrograhically, the intrusion is fine grained with disseminated pyrite throughout. Most of the primary minerals have been destroyed and replaced with epidote, chlorite, and iron-carbonate (after feldspar) alteration.

Geochemically, this intrusion has a flat rare earth elements (REE) pattern indicating a primitive, relatively unfractionated magma (Figure 39.2). Strontium depletion indicates alteration, likely by CO_2-rich fluids, which has been confirmed petrographically by the presence of carbonate.

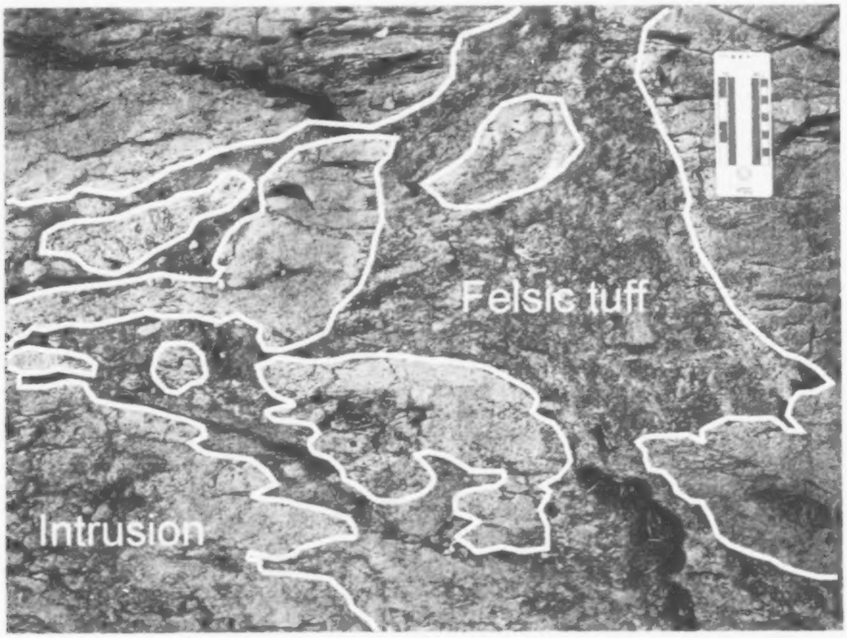

Photo 39.1. Outcrop appearance of the upper contact of the synvolcanic mafic intrusion showing irregular clasts indicative of incorporation of unconsolidated felsic tuff into mafic intrusion.

INTERMEDIATE INTRUSION

The later intrusion in the Genex area is intermediate in composition and occurs as a north-trending sill that obliquely cuts mine stratigraphy. The intrusion also has numerous east-trending dikes which stem from the main intrusive body, and commonly contains xenoliths of felsic breccia. The relative timing of this intrusion to both the volcanic stratigraphy and to the synvolcanic mafic intrusion is visible in both drill core and in outcrop in which the intermediate intrusion can be seen crosscutting the aforementioned rock units.

In outcrop, the intrusion is light grey on a fresh surface, and weathers white to tan. In drill core, the intrusion commonly has a reddish brown colour due to a high degree of iron-carbonate alteration. Grain size ranges from fine to medium grained, coarsening toward the centre of the sill; dikes emplaced higher in the mine stratigraphy locally contain quartz-filled amygdules (up to 30%). Spherulites are locally present (5 to 7%) in both outcrop and in drill core. Vague polygonal joints are locally present, but are not as well defined as in the synvolcanic mafic intrusion. Zones of fracturing are visible in both drill core and in outcrop, and are interpreted to represent seawater interaction with the hot intrusion, and thus implying that the intrusion is high level (emplaced relatively close to the seafloor) and synvolcanic.

The lower contact of the intrusion is marked by small apophyses extending into the underlying rocks. The upper contact is gradational with a metres-wide mixed zone in which the intrusion and the overlying rocks are chaotically mixed. However, the blocks of felsic tuff caught up in the intrusion are intact, suggesting that they were lithified prior to incorporation (Photo 39.2). Thus, the intrusion is synvolcanic in its timing, but is slightly later than the mafic intrusion.

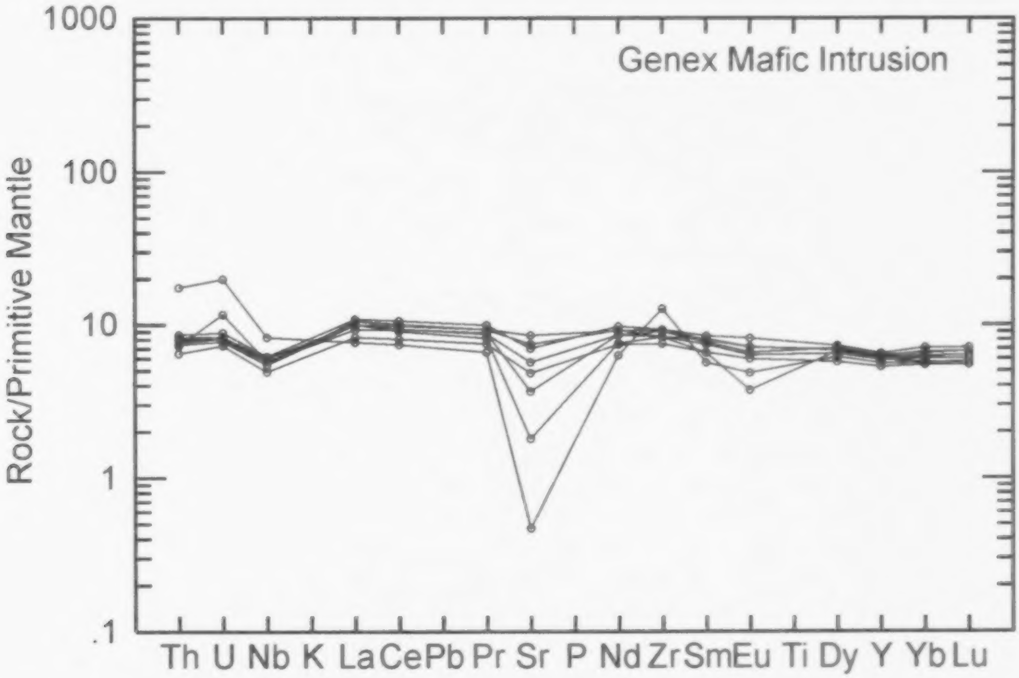

Figure 39.2. Primitive mantle normalized spider diagram for the synvolcanic mafic intrusion in the area of the Genex Mine. The vertical axis of the figure displays trace element values in ppm normalized to the primitive mantle values of Sun and McDonough (1989).

The numerous east-trending faults in the area do not cut the intrusion, but the intrusion does appear to be utilizing the faults as conduits as many of the dikes stemming from the main sill follow the faults. The intrusion is relatively unmineralized, except for sparse disseminated pyrite.

Petrographically, the intrusion is medium to fine grained with 1 to 5% spherulites. Most of the primary minerals have been destroyed and altered to chlorite, sericite, and iron-carbonate. The iron-carbonate alteration is more abundant in the intermediate intrusion than in the synvolcanic mafic intrusion, whereas epidote is much less abundant to absent in the intermediate intrusion relative to the mafic intrusion.

Geochemically, the REE pattern for the intermediate intrusion has a slightly steeper slope than that for the mafic intrusion, indicating that the later intrusion is more evolved (Figure 39.3). Comparison of REE trends for the intermediate intrusion to those of the Kamiskotia gabbroic complex, indicate that the intrusion is similar to the granophyric cap of the gabbroic complex (Campbell et al. 1981; Galley 1996). Strontium depletion is also present in this intrusion indicating some alteration, likely by CO_2-rich fluids. This has been confirmed petrographically by the presence of carbonate.

GENEX MINERALIZATION

The Genex deposit is a copper-zinc massive sulphide deposit that consists of 3 orebodies (the C-zone, H-zone, and A-zone) that were mined from 1964 to 1966. Over this time, approximately 242 tonnes (218 tons) of copper concentrate containing 21 to 27% Cu were produced (*The Northern Miner*, September 1, 1966, p.13; Middleton 1975; Binney and Barrie 1991). At the time the mine closed the ore reserves were estimated at 42 000 tons (38 000 t) grading 2.5% Cu (*The Northern Miner*, November 10, 1966, p.13, 20). Mineralization is contained within the matrix of a thin (approximately 0.5 to 3 m wide) pillow breccia (C-zone) and a lapilli tuff (H- and A-zones) which are in contact with a portion of the upper north-trending synvolcanic mafic intrusion. Numerous zones of shear-hosted mineralization are also present throughout the area in both mafic and felsic lithologies, and they tend to contain a higher zinc content.

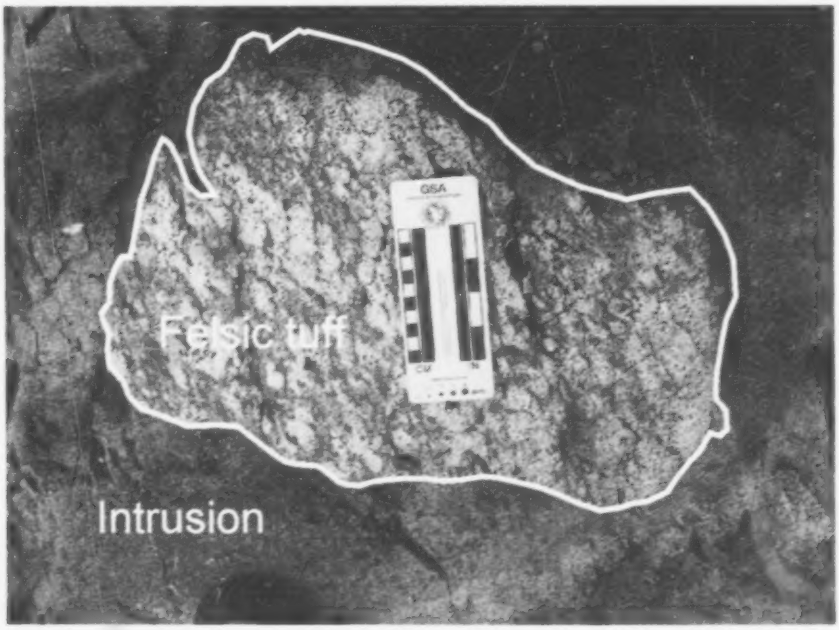

Photo 39.2. Outcrop appearance of the upper contact of the intermediate intrusion showing a xenolith of lithified felsic tuff.

C-Zone Mineralization

C-zone mineralization is contained within the matrix of a north-trending pillow breccia from which Genex Mines Ltd. mined 47 000 tons of ore at 2.92% Cu (the zinc was not recovered). All of the mill feed while the mine was in production came from the C-zone (*The Northern Miner*, September 1, 1966, p.13; Legault 1985). This orebody is distinct from the other two orebodies in that it is hosted in a mafic pillow breccia and is north trending. Preliminary assessment of the mineralization suggests that this orebody represents sub-seafloor replacement of sulphides from the surrounding mafic rocks by hydrothermal fluids into zones of higher permeability, with no true massive sulphide present. The higher grade and tonnage of ore in the C-zone compared to the H- and A-zones (felsic hosted), likely reflects the greater percentage of ferromagnesian minerals and magmatic sulphides preferentially enriched in copper, which is then available for leaching to the hydrothermal fluids (Barrie and Hannington 1999). The presence of disseminated and minor fracture-controlled sulphides in the mafic intrusion indicates that the sulphide-bearing fluids were present after the intrusion was emplaced. The intrusion itself may also have contributed a small amount of metals to the hydrothermal system, as has been observed in the Flavrian subvolcanic intrusion (in the Noranda, Quebec area) through isotopic and geochemical studies (Galley 1996). This hypothesis is yet untested.

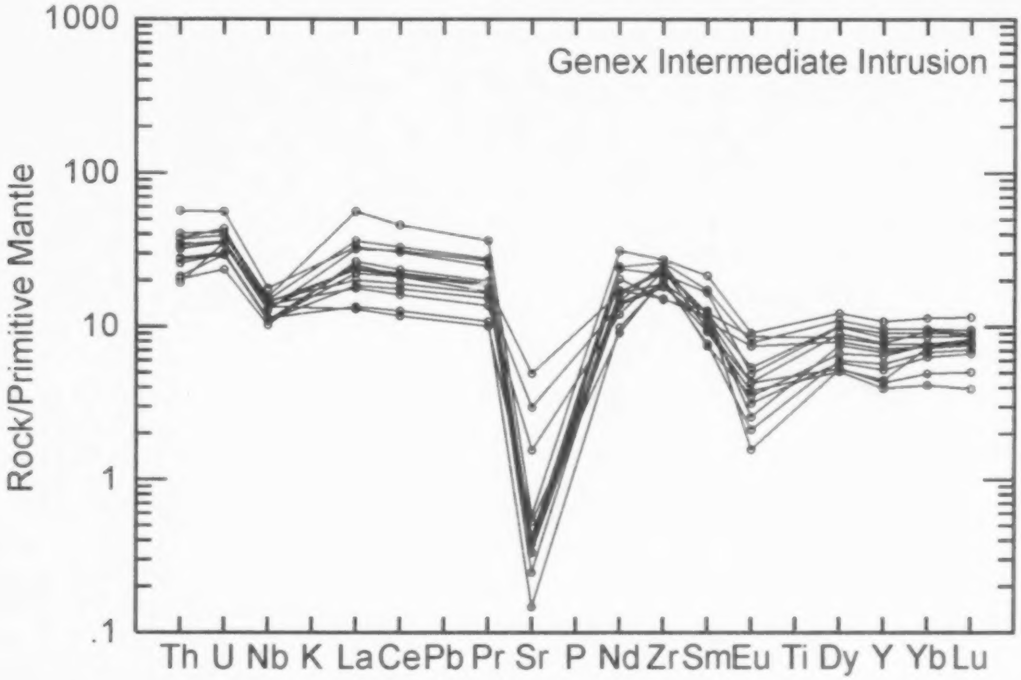

Figure 39.3. Primitive mantle normalized spider plot for the intermediate intrusion in the area of the Genex Mine. The vertical axis of the figure displays trace element values in ppm normalized to the primitive mantle values of Sun and McDonough (1989).

A-Zone and H-Zone Mineralization

The A- and H-zone mineralization is contained within the matrix of a felsic lapilli tuff breccia. Diamond drilling prior to production at the mine concluded that although the zones do contain zones of high-grade ore, the mineralization is too erratic to produce a significant tonnage of ore (Middleton 1975). Both of the sulphide lenses are disconformable and east trending, approximately parallel to faults in the area. Preliminary assessment of these two orebodies indicates that, like the C-zone mineralization, the mineralization is the result of sub-seafloor replacement of sulphides into zones of higher permeability, as the mineralization is contained solely within the matrix of a felsic lapilli tuff and/or tuff breccia. However, in this case, the sulphides appear to have also been deposited along fault zones, which likely represent conduits for the hydrothermal fluids.

INTRUSIONS AND MINERALIZATION

Mineralization at the Genex Mine is contained exclusively in the more porous matrices of pillow breccias and felsic lapilli tuffs, all of which are in contact with the upper synvolcanic mafic intrusion. However, the upper mafic intrusion is entirely void of mineralization which suggests that it was emplaced after mineralization. Minor fracture-controlled mineralization in the lower mafic intrusion and in the intermediate intrusion may suggest an earlier timing for these intrusions. This argument will be tested through further geochemical and petrographic analysis. Contact relationships in the intermediate intrusion indicate that this intrusion is later than the mafic intrusion and is not related to the Genex mineralization, but to the numerous east-trending faults that cut the mine stratigraphy.

The heat from the intrusions was not great enough to drive the hydrothermal system and enable hydrothermal fluids to leach metals from the wall rock, but it does indicate the presence of a high-temperature system (Hart, Gibson and Lesher 2004). Mapping of the spatial extent of the intrusions has been important in defining synvolcanic structures which may have served as conduits for hydrothermal fluids. During the coming year, geochemical and petrographic analysis of metal depletion in wall rocks, as well as possible identification of hydrothermal upflow zones will further advance these ideas.

Further analysis of field data, as well as analysis of geochemistry and petrographic work planned for the coming academic year will further our interpretations.

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40. Discover Abitibi. Base Metal Subproject 3. Geology of the Kidd–Munro, Tisdale and Kinojevis Assemblages in Munro and Currie Townships

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INTRODUCTION

In the second year of this two year project, the stratigraphy and the geochemical signatures of the volcanic rocks in Munro and Currie townships are being examined in order to better understand the base metal mineralization potential of the Kidd–Munro, Tisdale, and Kinojevis assemblages.

The Kidd–Munro assemblage (2718 to 2710 Ma) was examined in a transect in Munro Township where it is in fault contact with Porcupine assemblage sedimentary rocks (2690 to 2680 Ma) in the southwest corner of the township (Figure 40.1; U/Pb ages from Ayer et al. 2002, 2003a and references therein). Due to the incredible exposure of ultramafic flows and sills in Munro Township, numerous studies have been undertaken in the area (e.g., Pyke, Naldrett and Eckstrand 1973; Arndt, Naldrett and Pyke 1977; Johnstone 1991; Davis 1997; Houlé et al. 2000; Sproule et al. 2002). Munro Township hosts 6 mines: 1 asbestos (the Munro Mine), 2 polymetallic, Cu-Zn-Au-Ag (the Potter and Potterdoal mines), and 3 gold (the Croesus, American Eagle and White–Guyatt mines). Fourteen mineral occurrences and prospects are known in the transect area: 5 asbestos, 8 precious metal (Au±Ag) and 1 copper-cobalt (Cu-Co) (Table 40.1).

A second transect was examined in Currie Township where the volcanic succession consists of the Tisdale assemblage (2710 to 2703 Ma) in the north and central parts of the township overlain by the youngest formation (2702 to 2701 Ma) of the Kinojevis assemblage in the south (Ayer et al. 2002). In detail, the Bowman formation (Goodwin 1977, 1979; Jackson and Fyon 1991) of the Tisdale assemblage in Currie Township consists of mafic volcanic rocks overlain by the Marker formation which has an age of 2703.7±3.9 Ma (Ayer et al. 2002) and consists largely of calc-alkaline tuff and tuff breccia (MERQ–OGS 1983). This unit is in turn overlain by the Garrison formation (Goodwin 1977, 1979) of the Kinojevis assemblage (Figure 40.2). The Garrison formation is the stratigraphic equivalent of the Hébécourt formation of the Kinojevis assemblage in Québec (Goutier 1997). The Currie base metal showing (also known as the Tillex) is sediment-hosted mineralization within the Marker formation; the other showings in the township are gold, vein-replacement mineralization (Table 40.2).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.40-1 to 40-10.

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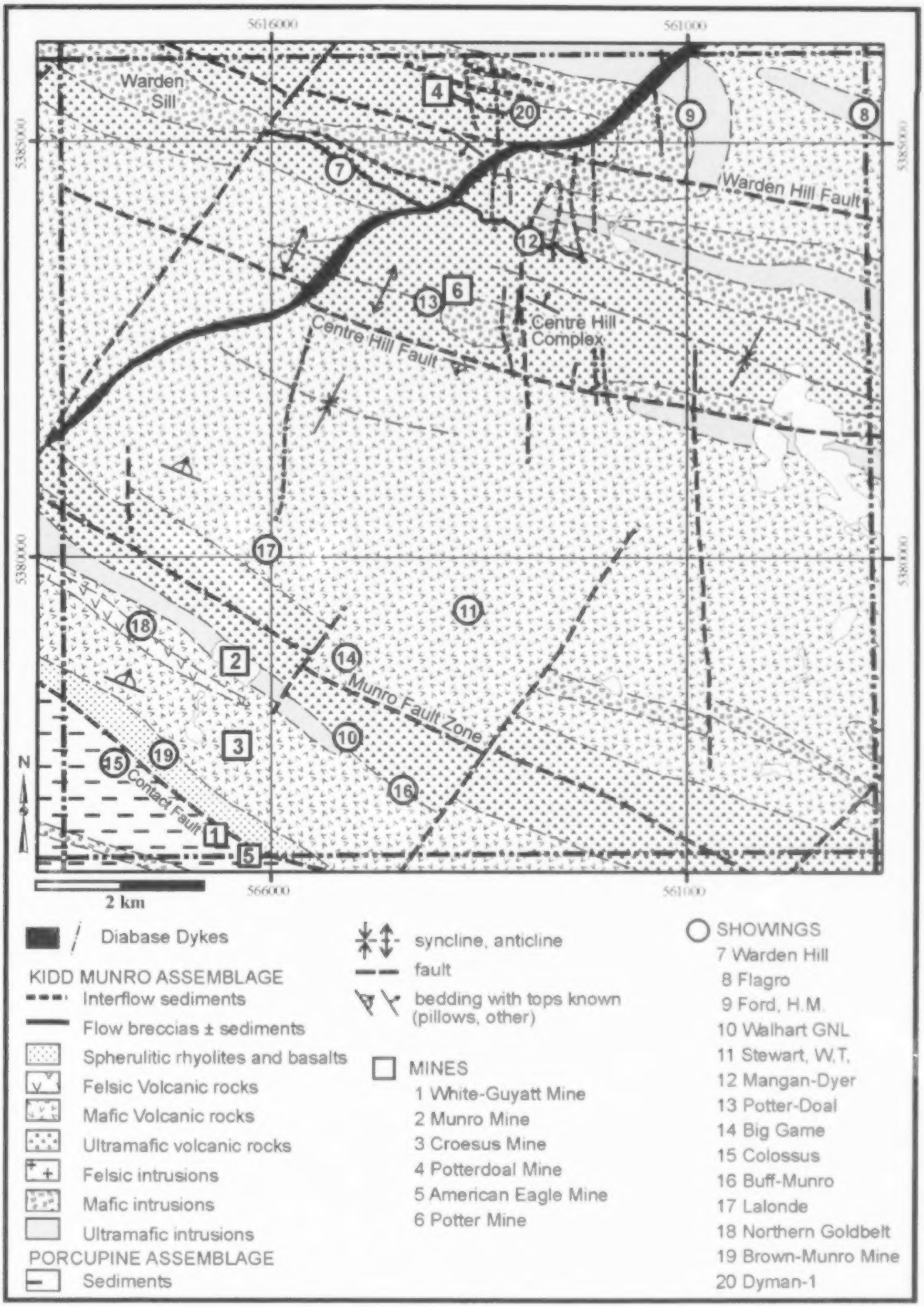
5616000
561000
5385000
5380000
566000
561000
Warden Sill
Warden Hill Fault
Centre Hill Fault
Centre Hill Complex
Munro Fault Zone
Contact Fault
N
2 km
Diabase Dykes
KIDD MUNRO ASSEMBLAGE
Interflow sediments
Flow breccias ± sediments
Spherulitic rhyolites and basalts
Felsic Volcanic rocks
Mafic Volcanic rocks
Ultramafic volcanic rocks
Felsic intrusions
Mafic intrusions
Ultramafic intrusions
PORCUPINE ASSEMBLAGE
Sediments
syncline, anticline
fault
bedding with tops known (pillows, other)
MINES
1 White-Guyatt Mine
2 Munro Mine
3 Croesus Mine
4 Potterdoal Mine
5 American Eagle Mine
6 Potter Mine
SHOWINGS
7 Warden Hill
8 Flagro
9 Ford, H.M.
10 Walhart GNL
11 Stewart, W.T,
12 Mangan-Dyer
13 Potter-Doal
14 Big Game
15 Colossus
16 Buff-Munro
17 Lalonde
18 Northern Goldbelt
19 Brown-Munro Mine
20 Dyman-1

Figure 40.1. General geology of Munro Township (*modified from* Ayer, Berger and Trowell (1999)).

Table 40.1. Mines and mineral occurences in Munro Township (*from* OGS 2002a). Numbers keyed to Figure 40.1.

Mine or Mineral Occurrence	Name	Commodity	Deposit Type	Mineralization Type
1	White-Guyatt Mine	Au	Mine	Vein / replacement deposits
2	Munro Mine	Asbestos	Mine	Mafic to ultramafic volcanic and intrusion associated
3	Croesus Mine	Au, Ag	Mine	Vein / replacement deposits
4	Potterdoal Mine	Cu, Zn, Ag, Au	Mine	Volcanic associated
5	American Eagle Mine	Au	Mine	Vein / replacement deposits
6	Potter Mine	Cu, Ag, Au, Zn, Co	Mine	Volcanic associated
7	Warden Hill	Asbestos	Occurrence	Mafic to ultramafic volcanic and intrusion associated
8	Flagro	Asbestos	Occurrence	Mafic to ultramafic volcanic and intrusion associated
9	Ford, H.M.	Asbestos	Occurrence	Mafic to ultramafic volcanic and intrusion associated
10	Walhart GML	Au	Occurrence	Vein / replacement deposits
11	Stewart, W.T.	Au	Occurrence	Vein / replacement deposits
12	Manga–Dyer	Asbestos	Occurrence	Mafic to ultramafic volcanic and intrusion associated
13	Potter–Doal	Asbestos	Occurrence	Mafic to ultramafic volcanic and intrusion associated
14	Big Game	Au	Occurrence	Vein / replacement deposits
15	Colossus	Au	Occurrence	Vein / replacement deposits
16	Buf–Munro	Au	Occurrence	Vein / replacement deposits
17	Lalonde	Au	Occurrence	Unknown hard rock deposit type
18	Northern Goldbelt	Au, Ag	Occurrence	Vein / replacement deposits
19	Brow–Munro Mine	Au	Prospect	Vein / replacement deposits
20	Dyman-1	Cu, Co	Prospect	Unknown hard rock deposit type

Abbreviations: Ag, silver; Au, gold; Co, cobalt; Cu, copper; Zn, zinc

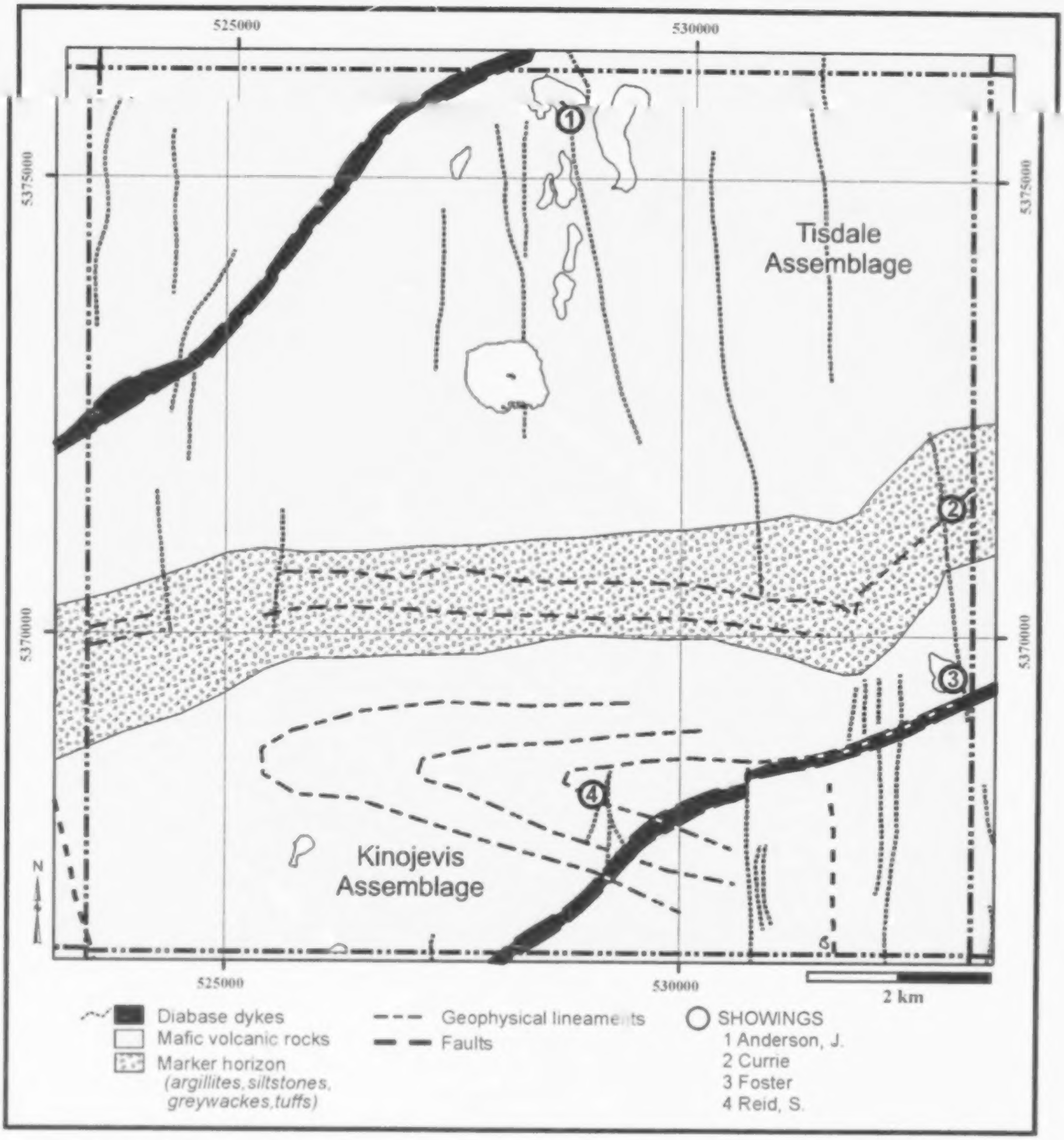
525000
530000
5375000
5370000
①
Tisdale Assemblage
②
③
④
Kinojevis Assemblage
N
525000
530000
2 km
Diabase dykes
Mafic volcanic rocks
Marker horizon (argillites, siltstones, greywackes, tuffs)
Geophysical lineaments
Faults
SHOWINGS
1 Anderson, J.
2 Currie
3 Foster
4 Reid, S.

Figure 40.2. General geology of Currie Township (*modified from* Ayer, Berger and Trowell (1999)). Geophysical lineaments *from* Ontario Geological Survey (2002b, 2004).

Table 40.2. Mineral occurences and prospect in Currie Township (*from* OGS 2002a). Numbers keyed to Figure 40.2.

Mineral Occurrence or Prospect	Name	Commodity	Deposit Type	Mineralization Type
1	Anderson, J.	Au	Occurrence	Vein / replacement deposits
2	Currie	Cu	Prospect	Sediment associated
3	Foster	Au	Occurrence	Vein / replacement deposits
4	Reid, S.	Au	Occurrence	Vein / replacement deposits

Abbreviations: Au, gold, Cu, copper

FIELD DESCRIPTIONS AND RELATIONSHIPS

Kidd–Munro Assemblage

The Kidd–Munro assemblage in Munro Township is dominated by mafic and ultramafic volcanic rocks, intruded by mafic and ultramafic dikes and sills; felsic volcanic rocks are very rare (*see* Figure 40.1; Satterly 1952a, 1952b; Johnstone 1991; Barrie 1999; Ayer, Berger and Trowell 1999). Three major northeast-trending faults cut the stratigraphy, and are, from south to north, the Munro fault zone, the Centre Hill fault and the Warden Hill fault. The volcanic sequence is also folded along a series of northwest-trending anticlines and synclines; the southernmost of which is south of the Centre Hill fault. An anticlinal axis has been recognized in the Centre Hill Complex–Potter Mine area (Oliver, Rebagliati and Haslinger 1999; Gibson and Gamble 2000; Houlé et al. 2000). An inversion of younging direction between the areas of the Potter and Potterdoal mines indicates that a synclinal axis passes through the area.

South of the Centre Hill fault, mafic volcanic rocks dominate. The two bands of felsic volcanic rocks in Munro Township occur south of the Munro fault zone. Ultramafic volcanic rocks are most common north of the Centre Hill fault, and also occur in the immediate area of the Munro fault zone. Thick mafic and ultramafic sills intrude the volcanic pile, most notably north of the Centre Hill fault.
The two base-metal mines in the township (the Potter and Potterdoal mines) are located within the mafic rocks of the mafic to ultramafic volcanic sequence north of the Centre Hill fault.

SOUTH OF THE MUNRO FAULT ZONE

The stratigraphy south of the Munro fault zone strikes northwesterly and tops northeast. The lowest units, in faulted contact with sediments of the Porcupine assemblage, are interlayered basalts and rhyolites-dacites. The southernmost rhyolite is calc-alkalic (A.D. Fowler, University of Ottawa, personal communication, 2004) and has been sampled for U/Pb geochronology. It is a highly sericitized lobe-and-breccia facies flow. This flow is overlain by an enigmatic sequence of basaltic flows, and units that have been previously designated as spherulitic or variolitic felsic and mafic units. These rocks are tholeiitic in composition (A.D. Fowler, University of Ottawa, personal communication, 2004), extend across Munro Township for over 3 km and continue into Beatty Township (Barrie 1999). The mafic spherulitic and/or variolitic units locally appear to be pillowed; the felsic units appear to be lobe-and-breccia facies flows, but are notable in their high percentage of breccia relative to massive lava lobes and pods compared to most felsic flow complexes. The spherulitic units are overlain by an approximately 1 km thick sequence of subaqueous basalt flows, characterized by massive and pillowed lavas and flow breccias. The lavas are commonly amygdaloidal, locally extremely so, and some units have large table (shelf) quartz-filled amygdules. Thick units of flow and/or pillow breccias with a high percentage of hyaloclastite matrix occur. Above the basalts lies the Beatty rhyolite. In Munro Township, the Beatty rhyolite is a thin, 150 m thick unit which pinches out 3.5 km east of the Beatty–Munro Township boundary. The Beatty rhyolite extends a further 4.5 km west into Beatty Township (Barrie 1999) where an age of 2714±2 Ma has been obtained using U/Pb geochronology. This rhyolite is quartz and plagioclase phyric, and forms lobe-and-breccia facies flows with the lobes exhibiting flow banding. Approximately 350 m of basalt pillowed and massive flows, and breccias, one of which is spherulitic, overlie the Beatty rhyolite. The contact between these basalts and the overlying ultramafic to mafic flows is intruded by an ultramafic sill. The Munro fault zone cuts the ultramafic to mafic flow unit along strike, making outcrops of the unit rare. The flows, where observed, exhibited *in situ* polyhedral brecciation and incipient pillows. Small-scale spinifex was observed locally.

NORTH OF THE MUNRO FAULT ZONE AND SOUTH OF THE CENTRE HILL FAULT

A syncline has been interpreted between the Munro and Centre Hill faults (Satterly 1952a, 1952b; Johnstone 1991). The volcanic sequence on the south limb of the fold is indeed north facing. Most of the outcrops on the north limb were not accessible, but the anticline in the Centre Hill area gives tops to the south, and Satterly's facing directions in other areas were, in the vast majority of instances, confirmed in the field. The fold axis is, therefore, retained in this study.

The volcanic sequence consists of mafic massive and pillowed flows and flow breccias. These units are commonly amygdaloidal and rarely plagioclase phyric. Ultramafic units are rare. The volcanic rocks are intruded by minor mafic dikes and sills, and by quartz-feldspar porphyritic dikes. On the north limb of the syncline, immediately south of the Centre Hill fault, there is a small felsic to intermediate intrusion. There are few outcrops of this intrusion, but its extent is interpreted by use of the total field magnetic survey and the shadow magnetics (OGS 2002b, 2003). The only outcrop of the main body visited, showed the intrusion to be multi-phase. The rock consisted of igneous breccia containing xenoliths of volcanic rocks as well as other phases (ultramafic to felsic) of the intrusion itself. The abundance of quartz-feldspar porphyritic dikes on the outcrops in the vicinity of this intrusion suggests that the dikes are probably related to the intrusion. Although the contacts with the host rock were not exposed, and there is no U/Pb age for this intrusion, it is interpreted to be a late intrusion.

NORTH OF THE CENTRE HILL FAULT

The area north of the Centre Hill fault is of particular interest, as it hosts the 2 base-metal mines (the Potter and the Potterdoal mines). Both ore deposits are associated with mafic units within the ultramafic to mafic volcanic sequence of the area. The Potter Mine ore deposit occurs within volcaniclastic rocks: a fluidal fall breccia and a lapilli tuff, which have been intruded by synvolcanic dikes (Gamble and Gibson 2000a, 2000b; Tardif et al. 2000). These dikes commonly have amoeboid contacts and locally disintegrate into peperites (Gamble and Gibson 2000a). The Potterdoal deposit is less well constrained, but occurs at the contact between two mafic flows. It may be associated with a flow breccia. In both areas, argillaceous sediments have been incorporated in the mafic volcaniclastic rocks.

In the area of the Potter Mine, immediately north of the Centre Hill Complex, the stratigraphy is folded around a northwesterly trending anticlinal axis (Oliver, Rebagliati and Haslinger 1999; Gibson and Gamble 2000; Houlé et al. 2000). The Centre Hill intrusive complex cores the anticline, eliminating most of the stratigraphy underlying the ore-hosting volcaniclastic rocks to the south. Three units have been recognized in the area (Gamble and Gibson 2000a; Tardif et al. 2000): a lower komatiitic unit, a middle tholeiitic unit (the volcaniclastic rocks hosting the mineralization), and an upper komatiitic unit. The units overlying the volcaniclastic rocks are spinifex-textured komatiite flows. The facing direction at Pyke Hill is to the north, and the fold closes to the west with changes in facing direction from north- to south-facing, as seen in drill core and on surface exposures (Oliver, Rebagliati and Haslinger 1999; Gibson and Gamble 2000; Houlé et al. 2000).

The stratigraphy between the Potter and Potterdoal mines is folded around a synclinal fold axis as indicated by inversion of younging direction. In the Potterdoal Mine area, stratigraphic tops are to the south, indicated by the brecciated tops of thin massive ultramafic to mafic flows and by pillows in basalts. The northernmost units in the Potterdoal Mine sector are thick sills; the lower sill being ultramafic and the upper being gabbroic. The gabbroic sill encloses thin sequences of siltstones and cherts, which are parallel to the volcanic stratigraphy. These sediments were interpreted (Johnstone 1991) to be remnants of the stratigraphy into which the sill intruded. Above the gabbroic sill, to the south, is a sequence of mafic to ultramafic flows; a thin sequence of siltstones and cherts occurs at the sill–volcanic contact. The Potterdoal Mine lies along strike to a contact between two mafic flows. The overlying flow is variolitic. The contact between the two flows is marked by a flow breccia containing variable amounts of disseminated pyrite (up to 20% 1 mm pyrite, locally). Ultramafic flows overlie the variolitic basalt. These flows are of variable thickness; south of the Warden Hill fault, a sequence of 2.5 to 3.5 m thick massive flows with brecciated flow tops giving tops south was observed. The ultramafic volcanic sequence is intruded by the mafic Warden Hill sill; like the northern gabbroic sill described above, cherty sediments occur at the upper contact of the Warden Hill sill. Above the Warden Hill sill, the mafic to ultramafic flows are thick layered flows separated by flow breccias and interflow cherty sediments, which are variably mineralized with disseminated pyrite. The northern flow is gabbroic in nature, whereas the southern flow is peridotitic.

Currie Township

There is very little outcrop in Currie Township, and most of it is spatially associated with high-weathering diabase dikes; the volcanic rocks being exposed on the edges of the dikes (Leahy 1965a, 1965b). The Marker formation at the Tisdale–Kinojevis assemblages boundary does not crop out, but is known from drill core and geophysical data to cross the township in a west-southwesterly direction. The 2004 geophysical surveys show that the units of the Kinojevis assemblage, south of the boundary, are folded with the fold closure to the west (OGS 2002b, 2004). In the Tisdale assemblage to the north, there is no apparent folding. Within the Marker formation, the combination of the shaded relief magnetic map and a total magnetic field map shows thin magnetic highs that run parallel to it. The electromagnetic anomalies of the 2004 geophysical survey also follow this trend.

The volcanic rocks of the Bowman formation of the Tisdale assemblage in the northern part of the township are dominantly subaqueous mafic massive and pillowed flows. Pillow elongations and tops, where observed, indicate stratigraphy to be east to east-southeast trending with tops to the south. Quartz-feldspar and feldspar porphyry dikes are common in the area. Locally, they contain xenoliths of the basalts, and, in some cases, the dikes are fragmental, containing fragments of other porphyries.

The Marker formation of the Tisdale assemblage was observed only in drill core. It is characterized by argillites, felsic and intermediate tuffs, and greywackes. In drill-hole logs, mafic to intermediate flows have been described within the clastic sequence. They are, however, rare. Pyritic and graphitic varieties of argillite are observed. Tops, determined by grading in the sediments, are to the south. Quartz-feldspar and feldspar porphyry dikes constitute a large portion of the lithologies seen in core. All rock types (sedimentary, volcanic and intrusive) are generally moderately to highly deformed; it appears that the

Marker formation acted as a favourable site for a deformation corridor. It is also exhibits locally intense alteration; sericitization, silicification and carbonatization are the most common, with lesser chloritization. The contact between the Marker and Bowman formations of the Tisdale assemblage does not outcrop, and was not observed in drill core. The contact between the Marker formation (Tisdale assemblage) and the Garrison formation (Kinojevis assemblage) was observed in one drill hole and described in a second drill-hole log. In the observed case, the contact, and both the Garrison formation mafic volcanic rock and the Marker formation argillite, were highly deformed and altered, with the deformation and bedding at 40° to core axis. In the described case, the contact was intruded by a feldspar porphyry dike. The Marker formation hosts gold and base metal (polymetallic) mineralization, which has been interpreted as syngenetic (J.A. Ayer, OGS, personal communication, 2004).

The basalts of the Garrison formation (Kinojevis assemblage) in Currie Township are commonly plagioclase porphyritic, and moderately to highly deformed. In the most deformed zones, such as the nose of the fold, the deformation produces a bedded or banded appearance. Locally, pillows and flow breccias can be distinguished, but no tops could be determined in the area of the township that was accessible. The volcanic rocks are also cut by feldspar and quartz-feldspar porphyry dikes. Again, the porphyries locally contain xenoliths of wall rock or fragments of porphyries.

RECOMMENDATIONS FOR EXPLORATION

In Munro Township, the base metal deposits (Potter and Potterdoal mines) are spatially associated with mafic flows in a mafic to ultramafic volcanic sequence. In the case of the Potter Mine, the mineralization appears to be hydrothermally deposited within the volcaniclastic (fluidal fall breccia and lapilli tuff) units (Tardif et al. 2000). The Potterdoal deposit environment is less well constrained. It is considered to have formed at the same stratigraphic level as the Potter Mine (Epp 1997), and similar rock types, including mafic volcaniclastic rocks, are observed in the area. However, only a small percentage of the clastic rocks are presently interpreted to be volcaniclastic. Most of the clastic rocks are interpreted as tectonic breccias formed at a fault scarp (Epp 1997). As at the Potter Mine, argillaceous sediments have been incorporated into the volcanic rocks and peperitized synvolcanic dikes intrude the volcanic pile. The peperite dikes indicate vent proximity. Re-examining the mafic–ultramafic flow contacts, particularly those with known pyrite mineralization, for evidence of vent proximity is recommended, as is re-examining the gabbroic sills interlayered with fine-grained clastic and cherty sediments to determine if they are indeed sills, or may be thick-layered flows like those south of the Potterdoal Mine.

In Currie Township, at the Tisdale assemblage–Kinojevis assemblage contact, gold and base-metal (polymetallic) mineralization is hosted by the Marker formation. Although the mineralization may have initially been syngenetic, the possibility that it has been, in part, remobilized by the deformation should be examined. In particular, the relationship, if any, to the deformation corridor of the Porcupine–Destor fault should be determined.

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41. Discover Abitibi. Gold Subproject 1. Protracted Structural Evolution of the Timmins–Porcupine Gold Camp and the Porcupine–Destor Deformation Zone

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INTRODUCTION

Classically, multiple deformation events have been recognized in the Timmins area, with the North and South Tisdale Anticlines and the Porcupine Syncline (Ferguson et al. 1968) all being truncated by the unconformity along the northern contact of the Timiskaming assemblage. Deformation postdating these folds is shown by later folding and faulting of the Timiskaming assemblage sedimentary rocks. However, only a single foliation has been distinguished (Brisbin 1997; Ferguson et al. 1968) across the area (Tisdale, Deloro, Mountjoy, Whitney, Hoyle townships), and these folds have not been rigorously assigned to specific fabric generations. The work reported here presents the evidence for recognition of four important foliation generation events (plus two late crenulations) in this area, and uses these foliations to assign folds to their appropriate generation. Combined with recent geochronological data, a more detailed structural model is proposed, in order to refine the understanding of the sequence of structural-metasomatic-gold events, and their timings, implicated in the development of the giant gold deposits in the Timmins gold camp.

PRE-D1 DEFORMATION: TELESCOPING OF STRATIGRAPHY

In the North Tisdale Anticline, Hersey Lake Formation komatiites and a thin sequence of basalts both belonging to the lower part of the Tisdale assemblage are present, whereas the upper Tisdale assemblage basalts (Ferguson et al. 1968) are absent with the Tisdale assemblage being overlain by the Porcupine assemblage sediments (Figure 41.1). Either these upper Tisdale assemblage basalts were not deposited in these localities, or they were excised by early (extensional?) faulting. Any such early faults would have been folded in later deformation events. No fabric has been identified as belonging to any such event.

D1 DEFORMATION

The S1 fabric associated with D1 folding is difficult to detect in the Timmins area and many past workers (e.g., Brisbin 1997; Piroschco and Kettles 1991) have suggested that D1 folds did not develop an axial planar cleavage. However, this work has shown that there are some areas where a weak S1 foliation

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p 41-1 to 41-10

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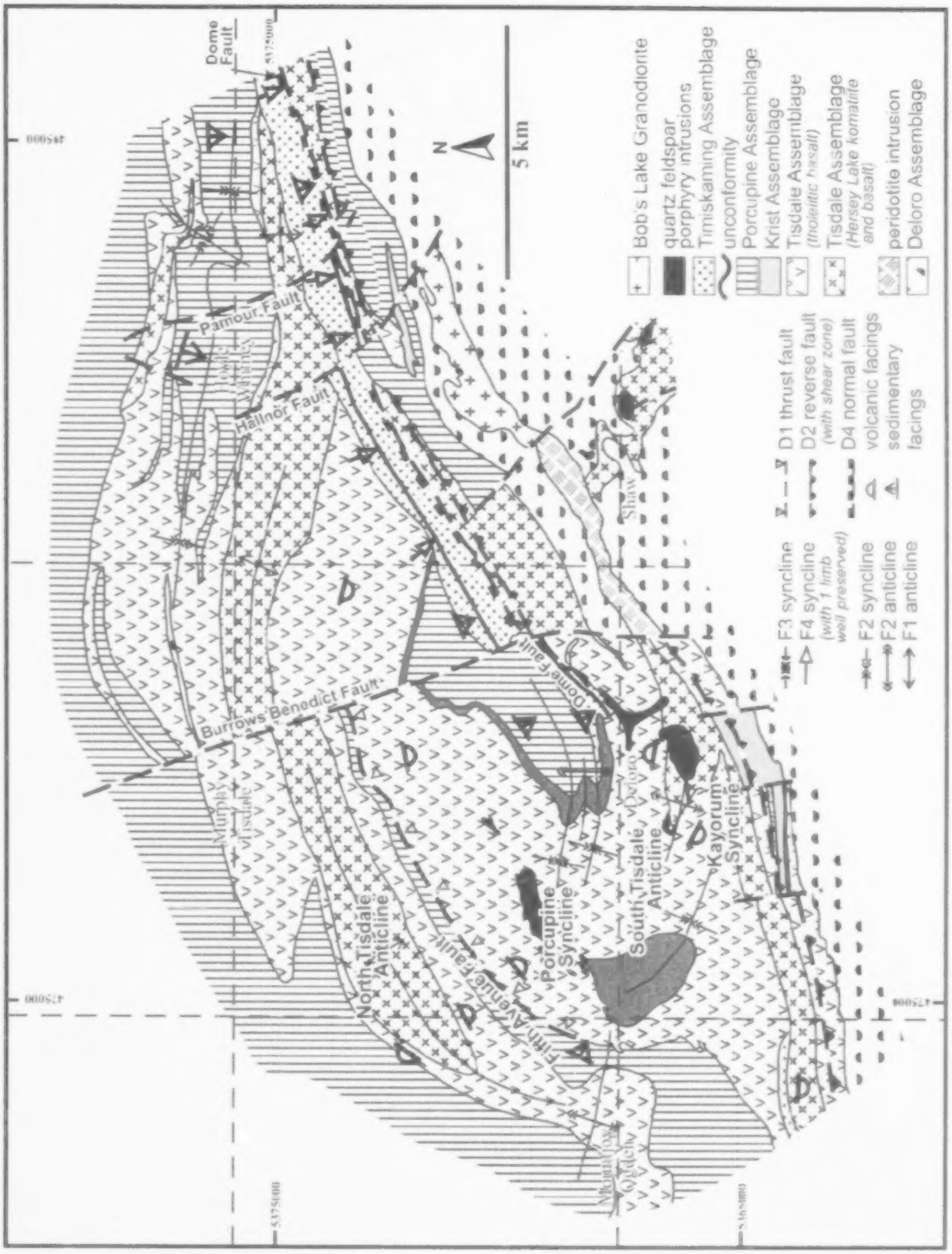
Dome Fault
Pamour Fault
Hallnor Fault
Hoyle
Whitney
Burrows Benedict Fault
Dome Fault
Shaw
Murphy
Tisdale
Deloro
North Tisdale Anticline
Fifth Avenue Fault
Porcupine Syncline
South Tisdale Anticline
Kayorum Syncline
Mountjoy
Ogden
N
5 km
495000
475000
5375000
5365000
Bob's Lake Granodiorite
quartz feldspar porphyry intrusions
Timiskaming Assemblage
unconformity
Porcupine Assemblage
Krist Assemblage
Tisdale Assemblage (tholeiitic basalt)
Tisdale Assemblage (Hersey Lake komatiite and basalt)
peridotite intrusion
Deloro Assemblage
D1 thrust fault
D2 reverse fault (with shear zone)
D4 normal fault
volcanic facings
sedimentary facings
F3 syncline
F4 syncline (with 1 limb well preserved)
F2 syncline
F2 anticline
F1 anticline

Figure 41.1. Generalized geological map of the Timmins area (Tisdale Township and parts of Deloro, Mountjoy, Ogden, Hoyle, Whitney townships) showing stratigraphic and structural anatomy of the gold camp.

can be recognized as the sole foliation, but it is more commonly preserved within the microlithons of the spaced S2 crenulation cleavage (discussed more fully below). The main F1 fold structure identified is the North Tisdale Anticline, which strikes northeast-southwest across the northern part of Tisdale Township, continuing eastward into Whitney Township (*see* Figure 41.1), where it is truncated by the Timiskaming unconformity in the vicinity of the Pamour Mine (Bateman, Ayer and Dubé 2003). Outward facing of pillows confirm that this is an anticline. A foliation has been recognized parallel to the axial plane of this structure, and has been designated as S1. S1 is recognized in both the Tisdale assemblage basalts and the unconformably overlying Krist formation of the Porcupine assemblage.

An important contact occurs between Tisdale assemblage basalts and Porcupine assemblage sediments in a belt on the south limb of the North Tisdale Anticline (*see* Figure 41.1). Strongly deformed graphitic schist (Photo 41.1) marks the southern contact of the Porcupine assemblage sedimentary units in two diamond-drill hole sections. This contact or fault dips about 70° toward 140° or 70° toward 340° (measured in two different cross sections), and so seems to crosscut in section the basalts of the Tisdale assemblage in the centre of the map area south of the fault. This fault may be a thrust, and has been tentatively termed the Fifth Avenue thrust. Ferguson et al. (1968) interpreted this belt of sediments as occcurring within the North Tisdale Syncline. However, the results of this project do not support such a fold, because all observed facings within these sedimentary rocks are to the south, including an outcrop on Wilcox Street in Timmins very near the southern contact of the Porcupine, indicating that there is no change in facing direction. D1 deformation postdated Porcupine sedimentation (2685±6 Ma: Ayer et al. 2003; Bleeker, Parrish and Sager-Kinsman 1999). In addition, the Central Tisdale Anticline (Ferguson et al. 1968) can not been verified as a single, simple structure. The basalts all face to the south on the northern limb of the Porcupine Syncline south of the belt of sedimentary rocks (*see* Figure 41.1), and elsewhere facings vary less regularly than suggested by Ferguson's map.

D2 DEFORMATION

D2 folds are major structures extending eastward into Whitney and Hoyle townships (Bateman, Ayer and Dubé 2003). The major foliation within the Tisdale assemblage basalts is typically S2, and consists of a near-ubiquitous spaced fracture or crenulation cleavage, with a spacing of cleavage folia of 1 to 2 mm. Typically, S1 can be recognized within S2 microlithons (similar to the relationship between S3 and S4). Distinction between S4 and S2 is based on overprinting (S2 is overprinted by S4 in a few areas near the Timiskaming syncline); orientation (S2 typically dips steeply north or northeast, whereas S4 dips to the north-northwest); S2 orientations are consistent with F2 folds, but not F4 folds; and distribution (S2

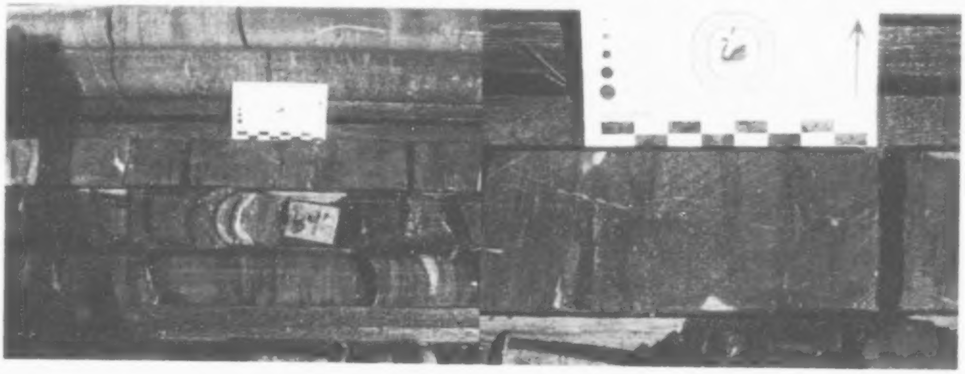

Photo 41.1. Graphitic phyllite, intense foliation, deformed pyrite lenses and later brittle fractures and veins mark the southern contact of a belt of Porcupine assemblage sediments and an extensive belt of Tisdale assemblage basalts. This probably marks the locus of D1 thrusting. Drill hole TGP002, 647 m.

orientations are not found within the Timiskaming sediments). S2 cleavage is axial planar to the Porcupine Syncline and is truncated to the east by the unconformity at the base of the Timiskaming sediments. S2 is the axial planar cleavage in the South Tisdale Anticline where bedding, S1 and quartz veins are folded by F2 at the Vedron property. The Kayorum Syncline is also interpreted to be an F2 fold as it is parallel to the South Tisdale Anticline. However, the S2 foliation was not common in this locality because of overprinting by intense later constrictional strain (discussed further below). The axial plane traces of this pair of F2 folds are curved, changing from a northwest strike in the north, to a more east-west strike adjacent to the Porcupine–Destor deformation zone (*see* Figure 41.1). The northeast-striking Porcupine Syncline may be partly a D4 structure (the along-strike continuation of the Timiskaming syncline), superimposed on early F2 elements shown by the smaller east-west folds at the hinge and along the northeastern limb of the Porcupine Syncline. Alternatively, the Porcupine Syncline may be solely an F2 fold with a strongly curved axial surface as in the South Tisdale Anticline. Together, these F2 folds may form a set of *en échelon* folds associated with left-lateral strike slip motion along the Porcupine–Destor deformation zone. D2 folding occurred after Porcupine assemblage deposition (2685±6 Ma) and before that of the Timiskaming assemblage (after 2673 Ma).

D3 DEFORMATION

D3 deformation is known from Hoyle Township, where S3 is recognized within metasedimentary rocks of the Timiskaming assemblage. It is preserved within S4 crenulations, where it is a penetrative foliation dipping moderately to steeply to the northwest. One major fold with a southwest-trending axial surface at the Hoyle Pond Mine (southeast Hoyle Township) and a few minor folds (1 to 100 m in amplitude) can be associated with this event. The larger scale significance of D3 deformation is not yet clear. It may be related to strike-slip movement around the change in trend of the Porcupine–Destor deformation zone during D3 to D4 strain. This is the subject of continued work.

D4 DEFORMATION

The major effects of D4 deformation are mostly recorded in the east, where S4 is the axial plane foliation to a large D4 syncline within the Timiskaming assemblage. S4 forms a strong crenulation cleavage with a foliation spacing of 2 to 5 mm. Otherwise, it is recognizable in the Tisdale assemblage lavas only in the immediate vicinity of the Timiskaming syncline. The Porcupine Syncline may be partly overprinted by F4 folding as its trend parallels the strike of the Timiskaming syncline in eastern Tisdale Township. There are small remnants of Timiskaming sediments in the Delnite and Buffalo–Ankerite pits and at the Naybob mine site (Deloro Township), which also have S4 foliation. D4 strain seems to be oblate in the east, but prolate strain is recorded in Tisdale Township. The age of D3 and D4 deformation is later than 2673 Ma (Ayer et al. 2003).

CONSTRICTIONAL STRAIN

Deformation in southern Tisdale Township is characterized by locally intense constrictional strain, which produced very strongly stretched pillows (Photo 41.2), amygdules and variolites in Tisdale assemblage basalts, lapilli in Krist formation volcaniclastics, and locally in pebbles in the Timiskaming assemblage sedimentary rocks. The event to which this constriction can be assigned (either D3, D4 or an additional event) is not yet established. Overprinting criteria are not useful as constriction postdating a foliation does not produce the same overprinting relationships as does one foliation overprinting another. The constrictional lineation does not lie within the plane of S3 after it has been rotated to remove the effects of D4 folding. This lineation lies more closely to, but not exactly within, S4. The constrictional strain does not appear to be consistent with F4, as the D4 fold axes have a subhorizontal plunge, and because D4 strain in the east appears to be typically pure flattening, not stretching. However, the zone of most intense constrictional strain is generally beyond the western end of the Timiskaming syncline. The constrictional lineation plunges eastward at an angle of about 45° and is always more shallow than the intersection lineation of S1 and S2, which plunges eastward at an angle of about 65°.

PORCUPINE–DESTOR DEFORMATION ZONE

Interpretations concerning the Porcupine–Destor deformation zone have long lacked data, detail and clarity because of its poor exposure. Maps of the area show the Porcupine–Destor fault as a discrete surface rather than a zone, and in a variety of locations. Diamond drilling indicates that the ductile component of the Porcupine–Destor deformation zone is a zone some hundreds of metres across consisting of anastomosing zones of high strain enclosing lower strain lozenges. The deformation zone occurs principally in ultramafic rocks of the Tisdale assemblage, but foliated rocks of the younger Timiskaming assemblage also record late movements. An estimate of offset is 10 km left lateral strike slip motion (based on offset of Krist formation, *see* Ayer et al. 2003) on a south-dipping fault (as defined by drilling). Over the summer of 2004, 12 diamond-drill cores were examined from a number of localities along its length within the map area. Orientations can generally be deduced from unoriented core in isolated holes based on the assumption that foliations dip steeply and not subhorizontally, but a few scissor holes allow for less ambiguous interpretations.

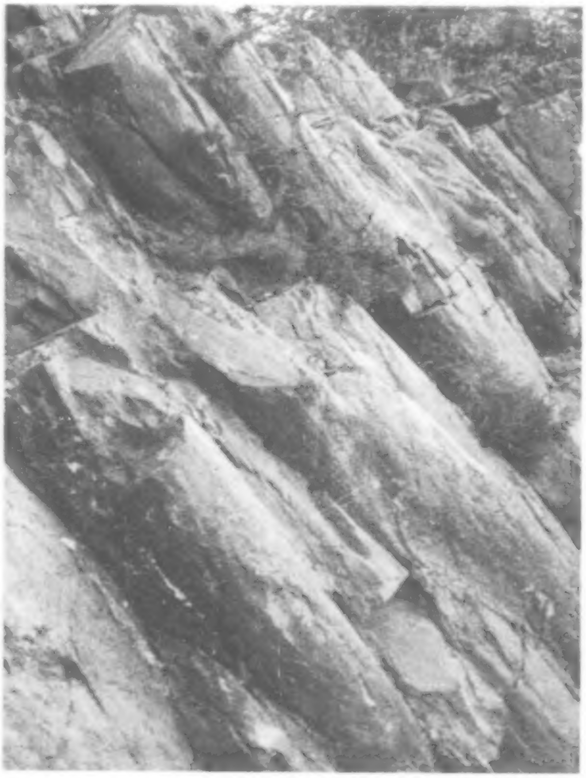

Photo 41.2. Strongly stretched pillows deformed in intense constrictional strain formed cigar-shaped structures. Station 04RJB0471. Tisdale assemblage basalts, Maclean Street, north of Timmins.

A three-stage kinematic history is proposed for this shear zone. Diamond-drill cores display C–S structures in which the S foliation dips steeply north and the C planes dip south, indicating dip-slip movement with south-block-up displacement along south-dipping shears (Photo 41.3). These are the dominant structure within the eastern drill holes. The ultramafic volcanic rocks are variably deformed, with alternating low-strain and high-strain intervals. This first phase may be attributed to D1 thrusting.

The above described S3 to S4 foliations were interpreted as indicating strike-slip movement. The Timiskaming assemblage sedimentary rocks show much lower strain than the Tisdale assemblage ultramafic rocks, suggesting that the bulk of Porcupine–Destor deformation zone strain predated Timiskaming sedimentation. Although sedimentary rocks and ultramafic lavas have very different competencies, in places, ultramafic volcanic rocks adjacent to the contact with Timiskaming assemblage rocks have a relatively low strain state compared with those further from the contact (Photo 41.4), indicating the ductile shear zone was not likely responsible for juxtaposition of the Timiskaming assemblage against the older Tisdale assemblage rocks. The sedimentary rocks have not recorded early thrusting strain. Moreover, in places there is an angular discordance in foliation orientation between Timiskaming assemblage and ultramafic Tisdale assemblage rocks. Poorly preserved, strike-slip C–S structures found in one hole in the west may also record this post-Timiskaming strike slip of movement, which is the second phase.

Brittle shears (the third and final stage) are also present, and postdate ductile shearing. In most locations, the southern edge of the Timiskaming sediments is marked by a brittle fault (a possible continuation of the Dome fault east of the Burrows–Benedict fault (*see* Figure 41.1). This fault contact is typically characterized by veining and brecciation (*see* Photo 41.4). The Dome fault approximately parallels the unconformity along the southern limb of the D4 syncline, but, in places, the north-facing unconformity between the Tisdale and Timiskaming assemblages is intact. Three-dimensional information derived from a number of scissor diamond-drill holes indicates that this faulted contact dips steeply north. It cuts the F4 folding and is therefore no older than a late component of D4. This is the same relative timing as the faulting associated with mineralization at the Pamour Mine (Bateman, Ayer and Dubé 2003), although normal displacement has not been described in faulting associated with this gold event. Together, the ductile and brittle shearing indicate early dip-slip movement and north-south bulk shortening, followed by D2 to D4 strike-slip faulting.

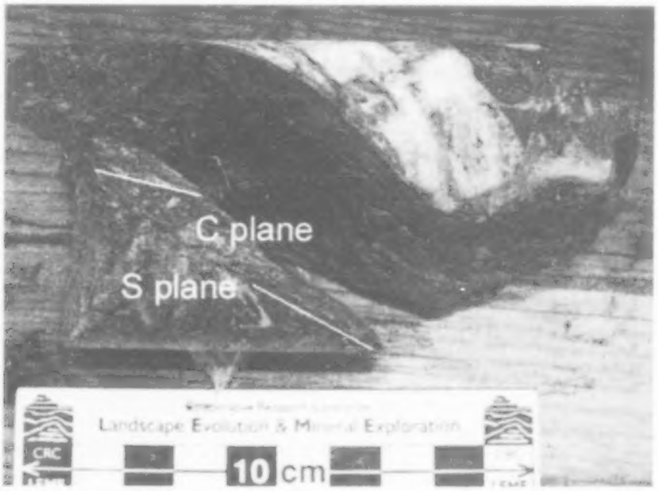

Photo 41.3. C–S fabric in intensely deformed Hersey Lake komatiites within the Porcupine–Destor deformation zone. These structures indicate dip-slip movement on a north dipping zone of high strain. Drill core, hole 18986, from near Pamour Mine.

TWO LATE CRENULATIONS

Two late crenulations are present. Neither has had any appreciable large-scale geometrical effect, and probably little role in mineralization. D5 kinks, folds and crenulations are best developed along the Porcupine–Destor deformation zone, where early foliation is especially well developed and hence more prone to further deformation. This crenulation cleavage dips steeply and strikes north-south. In Hoyle pit and elsewhere, minor examples occur where quartz veining has occurred during this event, which indicates late orogen-parallel shortening (Bateman, Ayer and Dubé 2003). D6 crenulations are a widely yet weakly developed, flat-lying set that may represent late orogenic collapse.

ABSOLUTE AND RELATIVE TIMINGS OF STRATIGRAPHY, DEFORMATION AND GOLD MINERALIZATION

In conjunction with detailed geological observations, uranium-lead (U/Pb) zircon geochronological results have helped to better constrain the age of the stratigraphic units hosting gold mineralization and the various deformation and mineralization events in the Timmins camp. The Tisdale assemblage ranges in age from 2710 to 2703 Ma (Ayer et al. 2002) and is unconformably overlain by the Porcupine assemblage. In southern Tisdale Township, the Porcupine assemblage consists of a lowermost unit of graphitic argillite and siltstone, conformably overlain by coarse felsic volcaniclastic rocks of the Krist formation (2688 Ma: Ayer et al. 2003), which, in turn, is conformably overlain by a thick succession of turbidites. Detrital zircons from two samples collected last summer provide new age constraints on the timing of the turbiditic unit of the Porcupine assemblage. A sandstone sample from the Hoyle formation north of the Pamour Mine yielded zircons indicating a provisional maximum ages for deposition of 2690 Ma and also contained an older detrital zircon with an age of 2725 Ma, which was most likely derived from the Deloro assemblage located south of the Porcupine–Destor deformation zone (Ayer et al. 2002). A second sandstone sample from the Whitney formation south of the Porcupine–Destor deformation zone in Whitney Township yielded detrital zircons indicating a provisional maximum age of

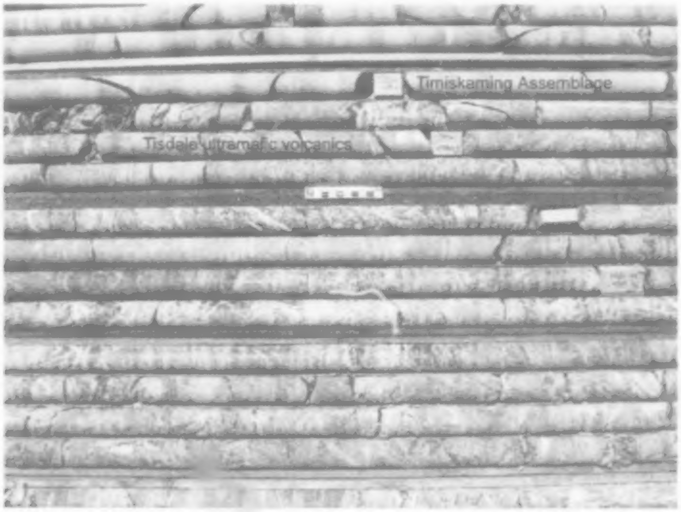

Photo 41.4. Brecciation and veining marks the contact between Timiskaming sediments and Hersey Lake komatiites within the Porcupine–Destor deformation zone. The ultramafic rocks are not highly deformed adjacent to the contact, but become more deformed further from the contact. The sediments are much less deformed than the volcanics. Drill hole 18964, south of Pamour pit, Whitney Township (Porcupine Joint Venture).

2688 Ma indicating that both sedimentary units are indeed part of the Porcupine assemblage. The Timiskaming assemblage unconformably overlies all older assemblages. The stratigraphic distribution of detrital zircons from various Timiskaming assemblage sedimentary samples suggests it was a long-lived basin as the lowermost Dome formation has a maximum age of 2679 Ma, while the uppermost Three Nations formation has a maximum age of 2670 Ma (Ayer et al. 2003). Southwest of the Pamour Mine, conglomerates of the Three Nations formation are also intruded by albitite dikes (Porcupine Joint Venture, unpublished data, 2004). At the McIntyre Mine, an albitite dike has an age of $2673\ ^{+6}/_{-2}$ Ma (Corfu et al. 1989). Here, the dikes cut the upper Tisdale assemblage basalts (ca. 2703 Ma) and quartz-feldspar porphyries (ca. 2687 Ma), but are themselves cut by gold veins. The above relationships suggests cessation of Timiskaming deposition and the onset of gold vein mineralization at a minimum age of about 2670 Ma. A sample of an albitite dike intruding the Timiskaming will be analyzed to attempt to provide a more precise age for this magmatic event and thus better absolute timing constraints on the timing of the Timiskaming and gold mineralization.

Both D1 and D2 are found in the Tisdale and Porcupine assemblages, but are truncated by the Timiskaming assemblage. Thus, these deformation events predated ca. 2679 Ma, the maximum age for deposition of the Dome formation. In areas affected by S1 to S2 foliation, principally in Tisdale assemblage basalts, intense ankerite alteration predates S2 foliation and chlorite foliation seams transect this alteration (Photo 41.5), leaving lenses of ankerite alteration enclosed by S2. Quartz veins were formed during early D2, with veins strongly folded in places by F2 (Photo 41.6). Elsewhere, veining may be contemporaneous with constrictional strain with subhorizontal ladder veinlets crosscutting ankerite alteration, indicating extension parallel to the constrictional lineation (Photo 41.7). These veins seem to be continuous with the principal quartz veins.

In areas characterized by S3 and S4 foliations, which occur both within the Timiskaming assemblage sediments (and more rarely in the older assemblages), quartz-carbonate-gold veining occurred late in D4 and S4 foliation development (Bateman, Ayer and Dubé 2003): most veins crosscut S4 foliation with a minimum of folding and dissolution of vein material across S4 foliation. Locally, some veins appear to have been emplaced during D5, which was presumably a late and essentially minor continuation of D4 deformation.

Thus, there seem to be 3 cycles of deformation, veining and gold mineralization, synchronous with D1, D2 to D3 and D4. Implications are that sequences of vein mineralogy are repeated in each event, and that these cycles are characteristic more of the local events and processes accompanying gold deposition than of larger scale fluid flow patterns and processes. Similar to Kalgoorlie (Bateman et al. 2001), this example of giant Archean lode gold mineralization is testament to the persistence of fluid flow and plumbing systems throughout protracted deformation.

Geochronological analyses using rhenium-osmium (Re/Os) on molybdenite at the University of Alberta has provided a method of determining the timing of gold mineralization that is more direct than by bracketing the age of the host rocks using U/Pb zircon methods. A molybdenite selvage to a quartz-dominated vein containing visible gold at the Dome Mine provided a model age of 2670±10 Ma and a sample containing molybdenite and chalcopyrite in altered Pearl Lake porphyry gave a model age of 2661±13 Ma for the age of the disseminated copper-gold mineralizing event (Ayer et al. 2003). However, as this latter age had a large error and was therefore inconclusive, a second sample was taken from adjacent core in the same diamond-drill hole, split into 2 aliquots and analyzed separately. The results were

Sample A	96.05 ppm Re	60.37 ppm ^{187}Re	2748 ppb ^{187}Os	model age 2672±10 Ma
Sample B	229.1 ppm Re	144.0 ppm ^{187}Re	6555 ppb ^{187}Os	model age 2672±10 Ma

Both of the second analyses are within the uncertainty of the first Pearl Lake porphyry sample analysis. The weighted mean of the above analyses is 2672±7 Ma, and this new date should be considered as the

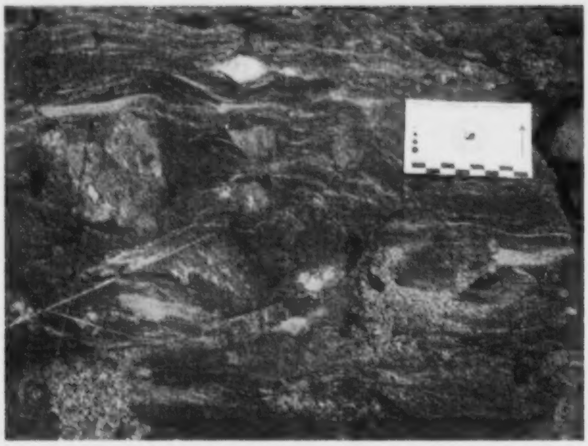

Photo 41.5. Blocks or lenses of early ankeritic alteration are transacted and wrapped by S2 foliation. Station 04RJB342, near Vedron.

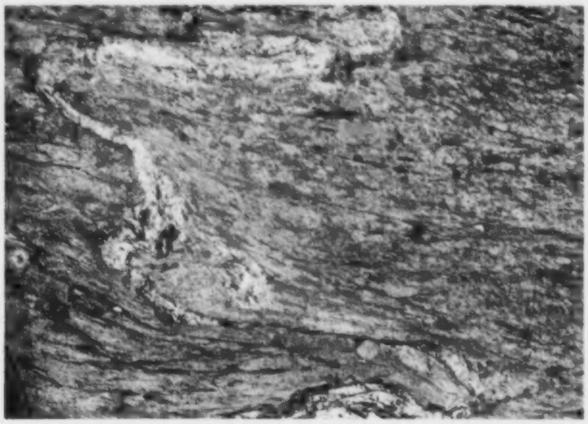

Photo 41.6. Quartz veins strongly folded by F2 and cut by S2 foliation. Station 04RJB0465, Vedron.

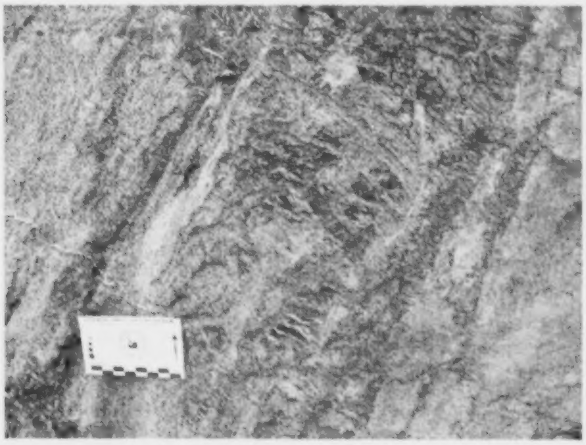

Photo 41.7. Blocks or lenses of early ankeritic alteration are cut by ladder quartz veins that are continuations of larger scale veins. The ladder veins are perpendicular to regional constrictional strain, and were opened during this event. Station 04RJB0331, on Highway 101 east of Timmins and south of the MacIntyre Mine headframe.

best indication of the age of the molybdenite and, therefore, the copper-gold mineralization in the Pearl Lake porphyry. The value of the above Re/Os model ages overlap in error, but in general supports the interpretation for an early disseminated gold-copper mineralizing event at the McIntyre Mine, followed by a later quartz-carbonate vein event at the Dome Mine.

ACKNOWLEDGMENTS

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42. Discover Abitibi. Gold Subproject 2. Geologic Mapping and Gold Mineralization Studies, Kirkland Lake Gold Camp (Gauthier and Teck Townships)

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INTRODUCTION

A two-year project funded under the Discover Abitibi Initiative started in 2003 with the goal of better understanding geological and structural controls on gold mineralization along the Kirkland Lake fault (Main Break) and Larder–Cadillac deformation zone. The project continued this summer with underground studies of gold mineralization and ore-controlling structures at the Macassa Mine and surface geological mapping along the Kirkland Lake gold trend (former Wright–Hargreaves, Lake Shore, Teck–Hughes, Kirkland Lake Gold and Macassa properties consolidated under ownership of Kirkland Lake Gold Inc, all in Teck Township). Several days at the beginning of the field season were spent completing the map done last year in Gauthier Township (Ispolatov, Lafrance and Dubé 2003). The L-zone stripping on the Upper Canada property was mapped in detail at 1:200 scale, and traverses were done in the eastern and northeastern portions of the 2003 map area to verify the location of lithostratigraphic contacts interpreted from aeromagnetic data (Ontario Geological Survey 2002).

TECK TOWNSHIP TRANSECT

General Geology of the Teck Township Transect

The Teck Township transect area comprises mafic metavolcanic rocks of the Tisdale and Kinojevis assemblages, and clastic metasedimentary and alkalic metavolcanic rocks of the Timiskaming assemblage (Ayer et al. 2002). The Tisdale assemblage is cut by the syenitic Murdock Creek pluton (Figure 42.1), and the Timiskaming assemblage is intruded by stocks, dikes and sills of augite syenite, syenite, and syenite porphyry. Two regional fault zone systems cut through the map area. The southern boundary of the Timiskaming assemblage corresponds to the Larder–Cadillac deformation zone (Wilkinson, Cruden and Krogh 1999). About 2 km to the north, the syenitic stocks are cut by the Kirkland Lake fault or Main Break, a brittle to brittle-ductile fault striking approximately 065° and dipping steeply to the south. Gold mineralization generally occurs along this fault and closely related subsidiary faults. Mineralization comprises relatively low-sulphide quartz veins, with gold and associated tellurides occurring mostly in the veins rather than in the altered host rocks. The presence of molybdenite, mainly along slip planes, is a distinct feature of Kirkland Lake ore (Thomson et al. 1950). In the currently active Macassa mine at the western end of the camp, the main ore-controlling structure is the ‘04 Break. The ‘04 Break is a northeast-striking fault, which is parallel to and located approximately 120 m north of the Main Break (Charlewood 1964; Still 2001). Ore-controlling faults and auriferous quartz veins are offset by major post ore-faults, including the Amikougami Creek and Lake Shore faults (*see* Figure 42.1). No economic mineralization has been found to date west of the Amikougami Creek fault.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.42-1 to 42-6.

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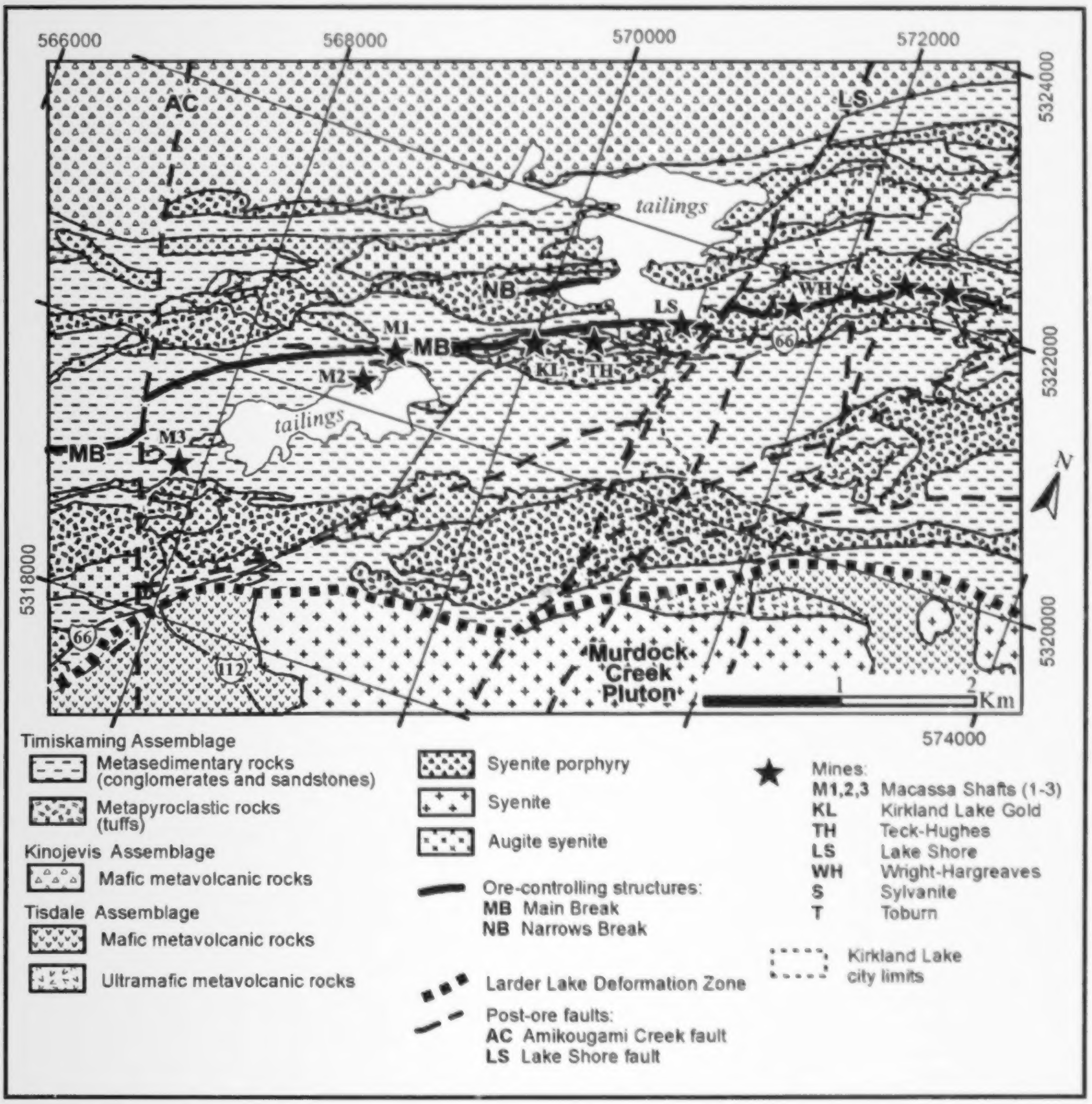
The history of gold discovery and production is discussed in detail in Thomson et al. (1950), Charlewood (1964) and Still (2001). Production commenced in 1915, and through the 20th century, the Macassa, Kirkland Lake Gold (later Kirkland Minerals), Teck–Hughes, Lake Shore, Wright–Hargreaves, Sylvanite and Toburn mines collectively produced 24 million ounces of gold (Still 2001). At present, Kirkland Lake Gold Inc. owns the Macassa, Kirkland Minerals, Teck–Hughes, Lake Shore, and Wright–Hargreaves properties and produces gold from Macassa number 2 and 3 shafts and Lake Shore ramp (www.klgold.com). Operations at Macassa, where most underground observations were made during this project, presently extend from the 3400-foot to 5000-foot levels.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112
Murdock Creek Pluton
1
2
Km
N
Timiskaming Assemblage
Metasedimentary rocks (conglomerates and sandstones)
Metapyroclastic rocks (tuffs)
Kinojevis Assemblage
Mafic metavolcanic rocks
Tisdale Assemblage
Mafic metavolcanic rocks
Ultramafic metavolcanic rocks
Syenite porphyry
Syenite
Augite syenite
Ore-controlling structures:
MB Main Break
NB Narrows Break
Larder Lake Deformation Zone
Post-ore faults:
AC Amikougami Creek fault
LS Lake Shore fault
Mines:
M1,2,3 Macassa Shafts (1-3)
KL Kirkland Lake Gold
TH Teck-Hughes
LS Lake Shore
WH Wright-Hargreaves
S Sylvanite
T Toburn
Kirkland Lake city limits

Figure 42.1. Generalized geological map of the Teck Township transect (*modified from* Thomson 1950b). Co-ordinates are Universal Transverse Mercator (UTM) North American Datum 1983, (NAD83), Zone 17.

Deformational Fabrics

Three generations of deformational fabrics were observed in the Timiskaming and Tisdale assemblages. The formation of fabrics postdates an earlier deformational event that occurred prior to deposition of the Timiskaming assemblage. Therefore, the earliest deformation fabric in Timiskaming assemblage rocks is a second-generation fabric (Wilkinson, Cruden and Krogh 1999). The nomenclature of the fabrics and other tectonic structures is identical with the one developed in 2003 for the Gauthier Township transect (Ispolatov, Lafrance and Dubé 2003).

S2, the earliest deformation fabric present in Timiskaming assemblage rocks (cf. Wilkinson, Cruden and Krogh 1999), is mainly developed in the Larder–Cadillac deformation zone at the contact between Timiskaming assemblage metasedimentary rocks (conglomerates, sandstones, and siltstones) and metavolcanic rocks (tuffs) and Tisdale assemblage mafic to ultramafic metavolcanic rocks. S2 generally strikes 075 to 090° and dips 70 to 80° to the south. It is a penetrative, steeply dipping foliation defined by flattened clasts in the conglomerates and tuffs and by alternating chlorite, sericite (±fuchsite) and carbonate layers in mafic to ultramafic metavolcanic rocks.

S3 is present in chlorite-fuchsite-carbonate-altered ultramafic rocks of Tisdale assemblage. It is expressed as a north-trending (350 to 005°) cleavage dipping moderately to steeply (50 to 70°) to the east and axial planar to east-southeast plunging symmetric and Z-asymmetric folds.

S4 is the most common deformation fabric in the Timiskaming assemblage rocks. It generally strikes 040 to 055° and dips steeply to the southeast or northwest. Along the Larder–Cadillac deformation zone, S4 is a spaced crenulation cleavage overprinting S2. S4 is weakly developed in the centre of the map area, but it increases in intensity in Timiskaming assemblage metapyroclastic and metasedimentary rocks north of the Kirkland Lake fault, where S4 forms a discrete spaced cleavage, which is generally oriented counterclockwise to bedding and axial planar to Z-shaped folds.

Kirkland Lake Fault (Main Break) and '04 Break

The Kirkland Lake fault is exposed underground at the Macassa Mine (eastern sections), and at surface on the Wright–Hargreaves and Lake Shore properties. Unmineralized portions of the fault were observed at the 4500-foot level of the Macassa Mine, in proximity to shaft number 2. At this location, the fault dips approximately 70° south and consists of a single 7 to 10 cm wide chloritic gouge band, and, less commonly, of a wider (30 to 50 cm) zone of brecciated rocks and branching chloritic slips.

At surface, the Main Break is best exposed on the Lake Shore property, east of former shaft number 5. It consists of several south-dipping (75 to 80°), 10 to 25 cm wide deformation bands, characterized by strong sericitic alteration. These bands show an internal foliation oriented oblique to their boundaries, both in plan and cross-section view. In plan view, the foliation is oriented at 15 to 20° counterclockwise to the boundaries of the bands; in cross-section view, the foliation dips steeper (or even shows vertical orientation or steep north dips) than the deformation bands. The orientation of the foliation suggests reverse-dextral (south side up and to the west) slip along the Main Break. As extensive sericitization was previously documented to be related to gold mineralization (e.g., Thomson et al. 1950, p.122), gold was likely deposited during reverse-dextral shear along the fault.

The '04 Break is observed underground at the 3800-, 4200-, 4500-, 4750-, and 4900-foot levels of the Macassa Mine. It is similar in orientation (strike ~070°, dip 60 to 70° south) to the Main Break, and is defined by narrow (2 to 10 cm) chloritic bands and locally wider (20 cm to 1 m) breccia zones, as the Main Break. The '04 Break is presently the main mineralized structure at the Macassa Mine. Other, subsidiary, ore-controlling structures include the South Break, '05 Break, and No. 6 Break (Still 2001). The No. 6 Break apparently splays from the '04 Break above the 4250- foot level. It strikes approximately

070°, dips 40 to 55° to the south, and diverges from the '04 Break with depth (Still 2001). The wedge-shaped block between the 4250-foot and 4500-foot levels confined by the '04 Break and No. 6 Break is the host of several economically important ore zones (Still 2001). In this study, the No. 6 Break was examined in stope 4225 (above the 4250-foot level), where it occurs as a narrow (3 to 5 cm) chloritic fault separating augite syenite (footwall) and tuff (hanging wall).

Gold-bearing Quartz Veins

Auriferous quartz veins were observed underground at the presently active 3400-foot to 5000-foot levels of the Macassa Mine, where they are hosted mainly by augite syenite, tuff and syenite porphyry. Mineralization at the mine is traditionally classified as "break ore", "vein ore" (hanging-wall and footwall veins) and "breccia ore" (Watson and Kerrich 1983; Still 2001). Of these 3 ore types, break ore and vein ore (hanging-wall veins) were examined. Breccia ore (i.e., altered, silicified and strongly fractured rocks with pods and lenses of quartz between major faults: Watson and Kerrich 1983; Still 2001) was not accessible at the time of the study. All occurrences of break ore observed in this work consist of quartz veins within or in the immediate proximity of the '04 Break.

Veins localized along the '04 Break generally dip 60 to 70° south (parallel to the host structure) with local shallower and steeper dips. The orientations of the hanging-wall veins vary from shallowly (10 to 35°) to steeply (60 to 70°) south dipping. Shallowly dipping (10 to 30°) veins tend to become steeper (50 to 70°) towards the north, as they converge with the '04 Break (Still 2001; M. Sutton, Kirkland Lake Gold Inc., personal communication, 2004). Veins hosted by tuffs are generally parallel to bedding. In addition to the south-dipping veins, there are also steeply north-dipping hanging-wall veins located in a wedge-shaped block between the '04 Break and its more shallowly dipping south splay, the No. 6 Break.

Both break-associated veins and variably oriented hanging-wall veins exhibit the same set of textures. There is no clearly defined tendency for veins of any particular orientation to be texturally distinct. Moreover, a single vein may change in texture from massive, to laminated and breccia type both along and across the strike. Laminated veins contain darker slip surfaces coated with fine molybdenite ± graphite, irregular bands of darker quartz, and 0.5 to 2 cm thick slivers of host rocks oriented parallel to the vein walls. The host rock slivers are locally interlayered with quartz bands of nearly equal thickness. Breccia veins consist of angular, unrotated clasts of host rocks cemented by quartz. In some veins, rock fragments are surrounded by a thin (0.5 to 1 mm) dark rim of fine molybdenite (?). Most veins comprise multiple quartz generations that vary in colour from milky white to almost black. In fractured and brecciated veins, later dark quartz commonly occurs along fractures and cements fragments of earlier white quartz. In some veins hosted by the '04 Break, brecciated quartz is cemented by chlorite. Although minor gold is associated with sulphides in altered host rocks (Thomson et al. 1950), economically significant gold mineralization appears to be largely related to gold contained in quartz veins rather that in sulphidized wall rocks.

Open-space-filling textures are observed in break-associated veins and both shallowly and steeply dipping hanging-wall veins. Most veins contain clusters and discontinuous bands consisting of white quartz crystals oriented at high angles to vein walls and later dark quartz filling interstices. In some breccia veins, fragments of host rocks are coated with radiating quartz crystals. The presence of open-space-filling textures (indicative of low effective confining pressure) in variably oriented veins, as well as the association of veins with largely brittle faults, imply that hydrothermal activity occurred at relatively shallow crustal levels.

Narrows Break Mineralization

Considerable confusion exists over the location of a structure called "Narrows Break" (Lackey 1990, p.74). The name is currently applied to mineralization exposed in a stripped area about 360 m north-

northwest of the former Kirkland Minerals main shaft and roughly 340 m north of the Main Break (S. Carmichael, Kirkland Lake Gold Inc., personal communication 2004).

Mineralization occurs as a zone of pervasive Fe-carbonatization and sulphidation (pyrite) localized at the southern contact of an augite syenite sill intruded in Timiskaming assemblage sandstones and reworked tuffs. No major ore-controlling fault-like structure is observed in the stripped area. Gold grades are relatively low, on the order of 0.15 ounces of gold per ton over 5 feet (1.5 m) (M. Sutton, Kirkland Lake Gold Inc., personal communication, 2004). The assay-defined ore zone roughly corresponds to a swarm of thin (1 to 10 mm) carbonate-quartz veinlets hosted by carbonatized and sulphidized rocks. The veinlets are zoned: carbonate lines the veinlet walls and quartz fills the centre of the veinlets. Fine-grained (<1 mm) macroscopically visible native gold occurs in some carbonate-quartz veinlets; gold may also be present in altered wall rocks, in association with disseminated pyrite. Veinlets show variable relationships with S4. Some veinlets are hosted by cleavage planes, others crosscut them, and some are crenulated parallel to the cleavage.

Relative Timing of Mineralization and Deformation

Our results to date suggest that Kirkland Lake mineralization was likely synchronous with the D4 deformational event. The reverse-dextral (south side up and to the west) slip along the primary ore-controlling structure, the Main Break, is kinematically compatible with the regional steeply dipping northeast-trending cleavage, S4, as both could have formed during regional northwest-southeast shortening. The mutually overprinting relationships between the carbonate-quartz veinlets and S4 at Narrows Break is consistent with temporal overlap of hydrothermal activity and D4.

Post-ore Veining

Non-auriferous post-ore veins occur along the ore-controlling faults (the Main Break and the '04 Break) and major post-ore faults. The post-ore veins either cut across or are parallel to auriferous quartz veins. They generally consist of translucent quartz and pink or white carbonate, with locally bands and rosettes of chlorite along the vein wall selvages. Some veins contain clots and patches of pyrite and chalcopyrite. Late, post-ore barite and gypsum (selenite) veinlets are also common.

Amikougami Creek Fault

Gold mineralization at the Macassa Mine and Kirkland Lake camp in general ends against the post-ore Amikougami Creek fault (*see* Figure 42.1). West of the fault, only a few isolated gold occurrences have been discovered so far. The sense and magnitude of the displacement along the Amikougami Creek fault are still poorly understood. Thomson's map shows roughly 270 m apparent sinistral (west-side south) offset of the Main Break along the fault (Thomson 1950a, 1950b). Underground exploration at the Macassa Mine revealed approximately 120 m of apparent sinistral displacement of the '04 Break, assuming that the east-northeast-striking structure encountered on the west side of the Amikougami Creek fault is the western continuation of the '04 Break. Exploration drifting on the 4750-foot level at the Macassa Mine traced this east-northeast-trending structure for up to 427 m, but no ore was found along the structure (Still 2001). As this structure is unmineralized, whereas mineralization along the '04 Break extends vertically for 980 m from the 3825-foot level to the 7050-foot level, the east-striking structure on the west of the fault may be not the continuation of the '04 Break, but is rather a parallel, unmineralized, fault (Still 2001). Determining the slip movement along the Amikougami Creek fault is therefore extremely important for discovering further '04 Break mineralization west of this fault.

The Amikougami Creek fault was examined underground on the 4750-foot level of the Macassa Mine. The fault strikes 339°, and it dips 70 to 75° east. It is a 1.3 m wide zone of chloritic gouge and breccia. Two thin (10 cm and 5 to 7 cm) diabase dikes are hosted by the fault. A syn-faulting foliation along the west margin of the fault zone is oriented clockwise of the fault walls suggesting strike-slip sinistral (west-side south) displacement. Fault-parallel striations plunge 10° north, which is consistent with subhorizontal strike-slip movement along the fault. Additional analysis of marker displacement is planned to further constrain the nature of the Amikougami Creek fault.

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43. Discover Abitibi. Gold Subproject 3. Regional Geological Assessment of Porphyry Intrusions Spatially Associated with Gold Deposits along the Porcupine–Destor Deformation Zone, Western Abitibi Subprovince, Timmins, Ontario

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INTRODUCTION

As part of the two-year Discover Abitibi Initiative, this article presents field observations of porphyry intrusions spatially associated with gold deposits along the Porcupine–Destor deformation zone (PDDZ) in the western Abitibi Subprovince. Numerous quartz-feldspar porphyry bodies were examined over the summers of 2003 and 2004. These porphyry bodies have been geographically grouped into 5 trends as shown on Figure 43.1. The trends include the central, northern, western, eastern and southern. Descriptions of observations for the central and northern trends were presented by MacDonald and Piercey (2003). These 2 trends were named the Vedron–Paymaster–Dome (central) trend and the Hollinger–McIntyre–Coniaurium (northern) trend previously. This article will report and discuss field observations collected on porphyry intrusions within the western, eastern and southern trends observed during the summer of 2004. In addition, preliminary U/Pb geochronology results on 2 porphyry intrusions collected during the 2003 summer will also be presented.

REGIONAL GEOLOGY

Most gold deposits in the Timmins camp are hosted within volcanic flows of the Tisdale assemblage (2710 to 2703 Ma) (Ayer, Ketchum and Trowell 2002). These flows range in composition from ultramafic at the bottom of the assemblage (Hersey Lake Formation) through tholeiitic (Central, Vipond and Gold Centre formations) in the middle to upper units of the Tisdale assemblage (Pyke 1982; Brisbin 1997).

Prior to gold mineralization, the Tisdale assemblage volcanic rocks were intruded by numerous porphyritic felsic bodies circa 2687 to 2691 Ma (Corfu et al. 1989; Ayer et al. 2003). Intruding the lower to middle units of the Tisdale assemblage (Hersey Lake through Vipond Formations), the porphyry intrusions both crosscut and conform to the older volcanic stratigraphy. Coeval with the porphyry intrusions, the felsic metavolcanic rocks of the Krist Formation (circa 2687 Ma) form the base of the Porcupine assemblage; this assemblage lies unconformably on top of the Tisdale assemblage within the Timmins camp (Ayer, Ketchum and Trowell 2002).

Both Porcupine assemblage turbiditic sedimentation (circa 2685 Ma) and Timiskaming assemblage fluvial sedimentation (circa 2674 Ma) postdate the porphyry intrusions within the Timmins camp prior to gold mineralization (circa 2670 Ma) (Bleeker, Parrish and Sager-Kinsman 1999; Ayer et al. 2003).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.43-1 to 43-7.

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QUARTZ-FELDSPAR PORPHYRY INTRUSIONS

Observations collected on the western, eastern and southern trends of porphyry intrusions are presented below.

Western Trend

The western trend of porphyry bodies includes felsic intrusions north of the PDDZ located west of the Mattagami River fault. Five intrusions were examined including the Bristol Township, Bristol Lake, Holmer, Thunder Creek and Southwestern Bristol Township porphyry and syenite intrusions.

The western trend of intrusions includes 2 types of intrusions: porphyries and syenites. The porphyry intrusions form an east-trending belt of intrusions. The largest porphyry body (Bristol Township porphyry) is located in eastern Bristol Township, west of the Mattagami River fault, and plunges towards the west (C. Dupont, Tom Exploration, personal communication, 2004). It has

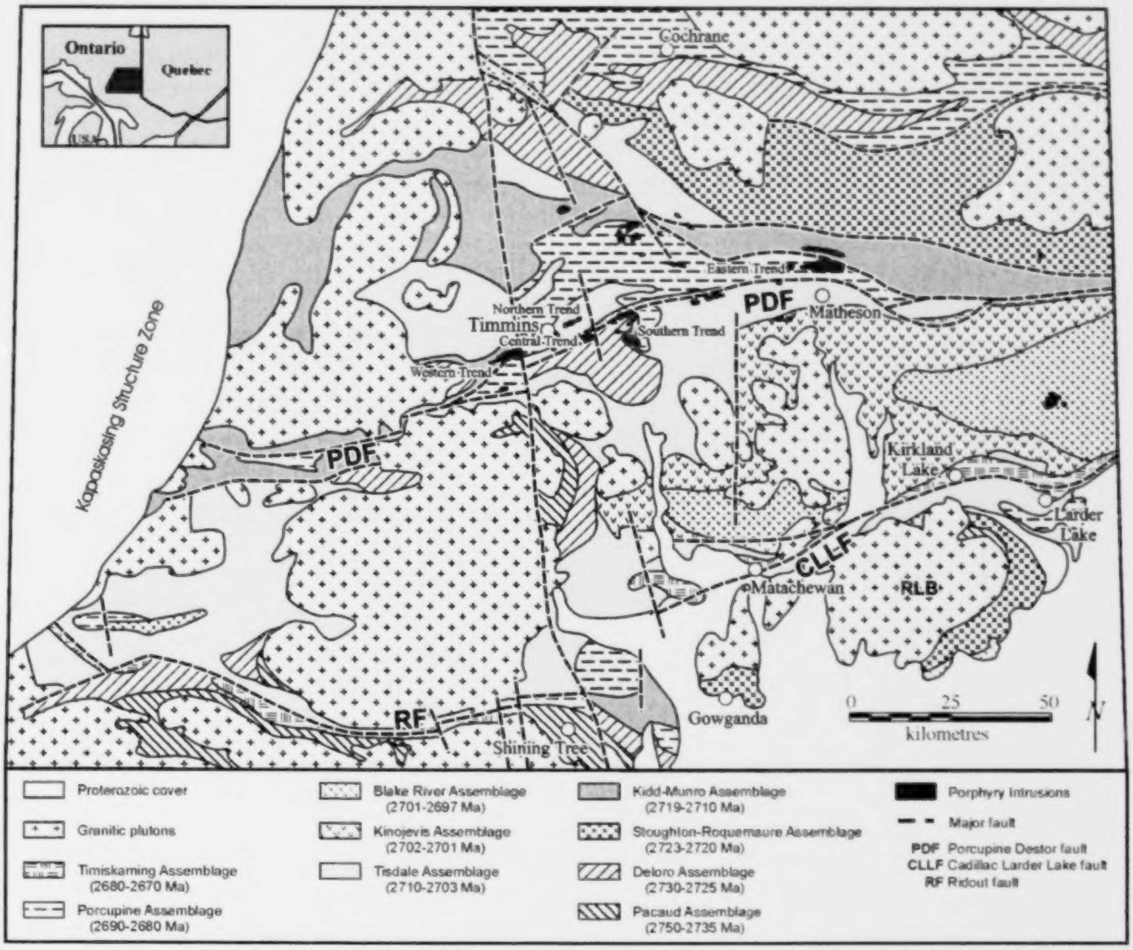
Ontario
Quebec
USA
Cochrane
Eastern Trend
PDF
Matheson
Northern Trend
Timmins
Central Trend
Southern Trend
Western Trend
Kapuskasing Structure Zone
PDF
Kirkland Lake
Larder Lake
CLLF
Matachewan
RLB
RF
Shining Tree
Gowganda
0 25 50
kilometres
N
Proterozoic cover
Granitic plutons
Timiskaming Assemblage (2680-2670 Ma)
Porcupine Assemblage (2690-2680 Ma)
Blake River Assemblage (2701-2697 Ma)
Kinojevis Assemblage (2702-2701 Ma)
Tisdale Assemblage (2710-2703 Ma)
Kidd-Munro Assemblage (2719-2710 Ma)
Stoughton-Roquemaure Assemblage (2723-2720 Ma)
Deloro Assemblage (2730-2725 Ma)
Pacaud Assemblage (2750-2735 Ma)
Porphyry Intrusions
Major fault
PDF Porcupine Destor fault
CLLF Cadillac Larder Lake fault
RF Ridout fault

Figure 43.1. Generalized geological map of the western Abitibi greenstone belt showing the 5 geographical groups of porphyry intrusions along the Porcupine–Destor deformation zone. The 5 groups include the central, northern, western, eastern, and southern (*modified from* Ayer and Trowell 1998; Ayer, Berger and Trowell 1999).

an age of 2687.7±1.4 Ma (Ayer et al. 2003) and occurs within the Porcupine assemblage metasedimentary rocks along the southern margin of mafic volcanic rocks of the Tisdale assemblage. Smaller porphyry dikes extend west (Bristol Lake and Holmer porphyries) from the Bristol Township porphyry along the Tisdale and Porcupine assemblages contact. The porphyry dikes generally have sharp margins (Photo 43.1A), although debris flows containing large porphyry blocks are present peripheral to the Bristol and Holmer porphyry intrusions. The syenite intrusions are located in western Bristol Township and include one medium-sized irregularly shaped body (Southwestern Bristol Township syenite) with small dikes extending north (Thunder Creek porphyry). Similar to the porphyry intrusions, the syenites also intrude near the Tisdale–Porcupine assemblages contact.

The western trend of porphyry intrusions generally consists of 1 to 5 mm quartz and feldspar (mostly plagioclase) phenocrysts in a felsic matrix. Pyrite is present in minor amounts disseminated throughout the porphyry intrusions. The large Bristol Township porphyry contains pyrite (±chalcopyrite) stringers and lenses up to a few centimetres in length. The syenite intrusions are fine- to medium-grained, equigranular to porphyritic, feldspathic intrusions. Disseminated pyrite is present in minor amounts within the syenite intrusions. The porphyry intrusions of the western trend show a weak to moderate sericite alteration along with minor chlorite. The large Bristol Township porphyry intrusion locally shows weak hematite alteration as well. The syenite intrusions show both weak to moderate hematite and ankerite alteration. Minimal quartz veining is present within the western trend of porphyry and syenite intrusions. Most veins are between 1 and 10 cm wide with minor pyrite (±chalcopyrite) enrichment in the selvages.

The western trend of porphyry and syenite intrusions is generally weakly deformed to undeformed. The only structural fabric observed in outcrop was a moderately developed nearly east-trending spaced cleavage exposed in the Bristol Lake porphyry.

Eastern Trend

The eastern trend of porphyries forms a belt of intrusions along the PDDZ from South Porcupine to Matheson east of the Burrows–Benedict fault. Eight intrusions were examined east of the Burrows-Benedict fault: Pamour porphyry, Bob's Lake granodiorite, Aquarius porphyry, Aquarius Mine porphyry, Homestead porphyry, Crowley porphyry, Pominex porphyry and Carr Township porphyry.

Only one of the intrusions was not directly hosted within the PDDZ or its splays (the Carr Township porphyry). All of the eastern trend intrusions are hosted within lower Tisdale assemblage ultramafic and mafic volcanic flows. The intrusions are globular to elongate in shape, and are often subparallel to stratigraphy. The contacts of the intrusive bodies are generally sharp except where breccia units mark a gradational contact between porphyry bodies and host mafic volcanic rocks (e.g., Aquarius and Carr Township porphyries).

The porphyry intrusions of the eastern trend typically consist of 1 to 5 mm phenocrysts of quartz and feldspar (dominantly plagioclase) in a quartzo-feldspathic matrix. The intrusions peripheral to the Aquarius Mine (Aquarius, Aquarius Mine, Homestead, Crowley and Pominex porphyries) have no quartz phenocrysts. Pyrite is disseminated throughout all of the intrusions and also occurs as clots up to a few centimetres in diameter (Photo 43.1B). Mica (muscovite and biotite) fragments up to 3 cm in diameter are present within the Pamour and Aquarius porphyries (Photo 43.1C). The eastern trend of porphyry intrusions have a range of alteration ranging from very weak to moderate. The most prominent alteration present in all of the intrusions is weak to moderate white mica alteration. Chlorite alteration is developed locally in most of the intrusions. Weak to moderate biotite (Pamour and Aquarius porphyries), hematite (Aquarius porphyry) and ankerite (Aquarius Mine porphyry) alteration facies are also present in the eastern trend of porphyry intrusions. Silicification and albitization are strongly developed in the

Aquarius, Aquarius Mine, Homestead, Crowley and Pominex porphyries near the Aquarius Mine site. Quartz veining with associated pyrite enrichment is present in most of the eastern trend of porphyry intrusions. As well, pyrite stringers are locally abundant within all of the porphyries.

Structural fabrics are only locally developed in the porphyry intrusion of the eastern trend. Typically, the margins of the intrusions show a weak to moderately developed foliation. The orientation of the foliation is unknown, since the porphyries were examined in drill core.

Southern Trend

The southern trend of porphyry intrusions includes intrusive bodies south of the PDDZ that are part of the swarm of porphyry intrusions that surrounds the Shaw Dome. This project focussed on examining 2 areas of this swarm: a porphyry dike swarm in northern Deloro Township, and the large Mt. Logano porphyry intrusions in northeast Shaw Township.

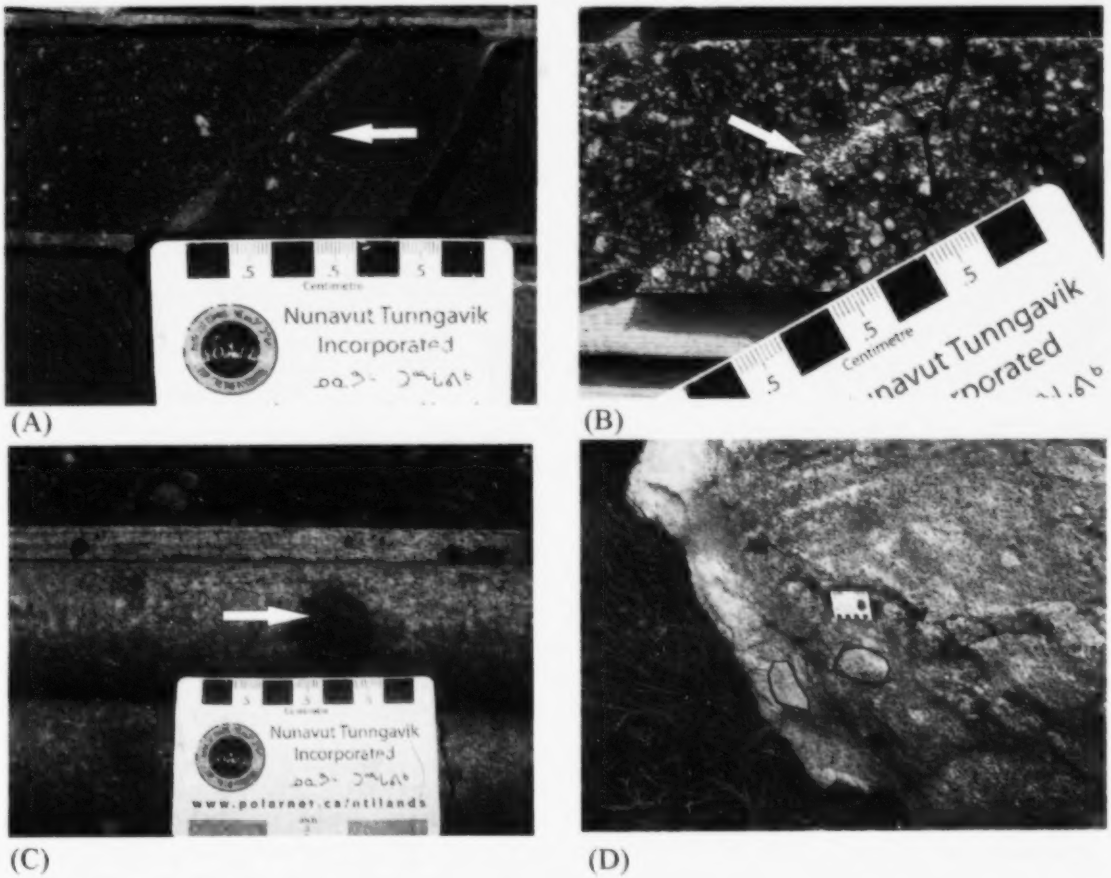

Photo 43.1. Photographs of observed features described in the text. A) Shape contact between a porphyry dike and mafic volcanic rocks, Holmer porphyry. B) Pyrite clot within relatively fresh (undeformed) Carr Township quartz-feldspar porphyry. C) Mica clot within the relatively fresh Aquarius feldspar porphyry. D) Porphyry fragments within the Mt. Logano porphyry near the western margin.

The porphyry dike swarm of northern Deloro Township consist of numerous east-trending dikes that are typically a few metres in width. These porphyry dikes have intruded at the top of the Deloro assemblage and the base of the Tisdale assemblage. The strike length of some dikes ranges from over a kilometre to only a few hundred metres. The Deloro Township porphyry dikes typically show sharp margins with the host volcanic rocks and appear to crosscut stratigraphy, although this relationship is not well exposed. The Mt. Logano porphyry consists of one large felsic intrusive body. Mt. Logano porphyry has intruded near the Tisdale–Deloro assemblages contact on the northeastern corner of the Shaw Dome. This elongate, 5 by 1 km long intrusion shows internal breccias within the porphyry body near the western margin (Photo 43.1D).

Both the porphyry dike swarm of Deloro Township and the large Mt. Logano porphyry contain quartz and feldspar (dominantly plagioclase) phenocrysts ranging from 1 to 5 mm. The phenocrysts are supported in a fine-grained, quartzo-feldspathic matrix. Minor disseminated pyrite is present all of the porphyries of the southern trend. The porphyries of the southern trend have both undergone white mica and chlorite alteration. The white mica alteration of feldspars is weakly to moderately developed in all of southern trend porphyry intrusions. Chlorite alteration is more localized and is typically only weakly developed. Although quartz veining with pyrite and chalcopyrite enrichment occurred in the mafic volcanic rocks peripheral to the porphyry dike swarm, only small, barren quartz veins are present within the porphyry intrusions. No sulphide enrichment is associated with the quartz veins within the porphyry; no veining is present in the Mt. Logano porphyry.

The porphyry dike swarm in Deloro Township has undergone the most deformation of the southern trend. The porphyry dikes show a moderately developed, steeply dipping spaced cleavage. Within the spaced cleavage, microlithons record an older, subparallel foliation. The spaced cleavage is also recognizable in outcropping of the Mt. Logano porphyry.

U/Pb GEOCHRONOLOGY: PRELIMINARY RESULTS

Samples of 2 porphyries were collected during the 2003 field season, including a quartz-feldspar porphyry from the eastern trend located southwest of the Pamour Mine and a sample from the Mt. Logano porphyry, south of the Porcupine–Destor fault. Samples were analyzed at the Jack Satterly Geochronology Laboratory at the University of Toronto following the methods of Davis and Lin (2003). Preliminary results are outlined below.

- *Sample 03PJM-131:* quartz-feldspar porphyry, PJV Drill Hole 18986, 340.8–392m (UTM NAD83 Zone 17: 489978E, 5373473N)
  This sample was collected to test whether the recently discovered Pamour porphyry of the eastern trend has the same age as those porphyry intrusions spatially associated with gold mineralization within the central and northern trends. This sample has yielded an imprecise age of ~2690 Ma; further fractions are required to tighten this age.
- *Sample 03LAH-0627:* Mt. Logano porphyry (UTM NAD83 Zone 17: 492156E, 5365021N)
  The Mt. Logano porphyry was sampled to test whether the felsic porphyries south of the PDDZ have the same age as porphyries north and within the PDDZ. A preliminary age of 2689.0±1.4 Ma has been obtained for this sample.

SUMMARY AND DISCUSSION

The porphyry intrusions of the western trend have similar primary mineralogy (quartz-feldspar), alteration mineralogy (sericite, ankerite and chlorite) and deformation (at least one generation) to the porphyry intrusions of the central and northern trends. Unlike the central and northern trends, however, the western porphyries show little association with gold mineralization. The smaller, more westerly porphyry dikes near the Holmer deposit contain little or no mineralization, and are not associated with gold mineralization proper (J. Samson, Lake Shore Gold, personal communication, 2004). The large Bristol porphyry shows moderate gold mineralization in sulphide-enriched zones; however, no high-grade zones are known to be associated with this large porphyry intrusion to date (C. Dupont, Tom Exploration, personal communication, 2004).

The two types of intrusions in the eastern trend have different associations with gold mineralization. The quartz-feldspar porphyries (Pamour and Carr townships) have similar primary and alteration mineralogy to the central and northern trend of porphyry intrusions (*see* MacDonald and Piercey 2003, for descriptions), but the Pamour and Carr Township porphyries exhibit less deformation when compared to central or northern trend quartz-feldspar porphyries. Notably, the Pamour porphyry has the same age as those in the central and northern trends (e.g., Corfu et al. 1989; Ayer, Ketchum and Trowell 2002, and references therein); however, it is not mineralized (W. MacRae, Porcupine Joint Venture, personal communication, 2003), unlike those in the northern and central trend (e.g., Preston–Paymaster porphyries at Dome). The Carr Township porphyry shows weak gold mineralization, but like the Pearl Lake porphyry of the northern trend, is copper enriched within hematite-altered zones. The feldspar porphyries of the eastern trend (Aquarius, Aquarius Mine, Homestead, Crowley and Pominex porphyries) only differ from the central trend porphyries by their lack of quartz phenocrysts. All of these porphyry intrusions show minor to moderate gold mineralization, but the highest grades are from the silicified and ankerite-altered Aquarius Mine porphyry (R. Norman, Kinross–Echo Bay Mines, personal communication, 2004).

Like the western trend of porphyries, the southern trend of porphyry intrusions is similar to the central and northern trends of porphyries in primary mineralogy, alteration mineralogy, age and deformation. No gold mineralization is associated with any of the southern trend porphyries; this may be the result of its location on the southern side of the PDDZ.

Observations from this research suggest that gold mineralization is most strongly correlated with the porphyry bodies in the Timmins camp that show intense sericite alteration coupled with moderate ankerite alteration. The presence of multiple porphyry bodies in intensely deformed areas of the belt also seems to be important in the development of the Timmins gold deposits (e.g., Hollinger-McIntyre and Dome). Even though most of the porphyry bodies examined show some gold enrichment, recent geochronology of the McIntyre and Dome gold mineralization events suggests a span of at least 15 million years between porphyry emplacement and gold mineralization, and, therefore, there is no genetic link between porphyry intrusions and gold mineralization (Ayer et al. 2003). Two possibilities remain for the strong spatial relationship between porphyry intrusions and gold mineralization, including 1) that gold mineralization developed during regional deformation because of the competency difference between the porphyries and the surrounding mafic volcanic rocks; and/or 2) that the porphyry intrusions and gold-bearing fluids utilized the same long-lived structure at different times.

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44. Discover Abitibi. Intrusion Subproject. Updates on Studies of the Clifford Stock and Blake River Group, Clifford Township

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INTRODUCTION

The Blake River Group in Quebec has produced over 3 million tonnes of Cu and Zn from volcanogenic massive sulphides (VMS) (Racicot 1990) in 17 past-producing deposits (Gibson and Watkinson 1990). Within the Noranda camp, the setting, style, distribution, and regional- to local-scale controls on deposit localization are well understood (e.g., Galley 1993, 2003; Gibson 1989; Gibson and Watkinson 1990; Hannington et al. 2003; Paradis et al. 1993; Péloquin et al. 1990). In contrast, the Blake River Group in Ontario has received little modern geological, geochemical, or isotopic study, although it lies just 50 km west of the Noranda mining camp. The intrusion subproject and base metals subproject (Ayer et al. 2003) was initiated to obtain a better understanding of the stratigraphy, volcanic setting, hydrothermal alteration, and subvolcanic intrusive rocks and their relationship to volcanogenic massive sulphide (VMS) and potentially gold deposits in the Blake River Group in Ontario.

In this paper, we provide an update on the field, geochemical, and isotopic research undertaken in 2003–2004. We will provide 1) an updated stratigraphic column and map for the Blake River Group in Clifford Township based on mapping completed in 2003; 2) new observations on the setting and styles of mineralization gleaned from drill core provided by Wallbridge Mining Company Ltd. in 2004 in Clifford Township, and surface observations in 2003–2004; 3) a preliminary assessment of geochemical data for the Clifford stock and related rocks, and rocks of the Blake River Group in Clifford Township; and 4) preliminary U/Pb geochronology results for rocks in Clifford Township.

GEOLOGY AND STRATIGRAPHIC RELATIONSHIPS

The geological and stratigraphic relationships between the Blake River Group and Clifford stock and related rocks in Clifford Township were determined via geological mapping in 2003 and augmented by drill-core studies in 2004 (Figures 44.1 and 44.2). Clifford Township is dominated by volcanic and subvolcanic rocks of the Blake River Group, felsic intrusive rocks of the Clifford stock and associated dikes, and Paleoproterozoic dikes of the Matachewan dike swarm (*see* Figures 44.1 and 44.2).

In the study area southwest of the Clifford stock, the Blake River Group consists of an outward younging succession of basaltic-andesite, andesite, felsic volcaniclastic rocks (*see* Figure 44.1). The lowermost packages consist of pillowed to massive, basaltic andesite to andesite that is amygdaloidal and variably plagioclase porphyritic; where porphyritic plagioclase crystals are 2 to 3 mm long and relatively

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.44-1 to 44-14.

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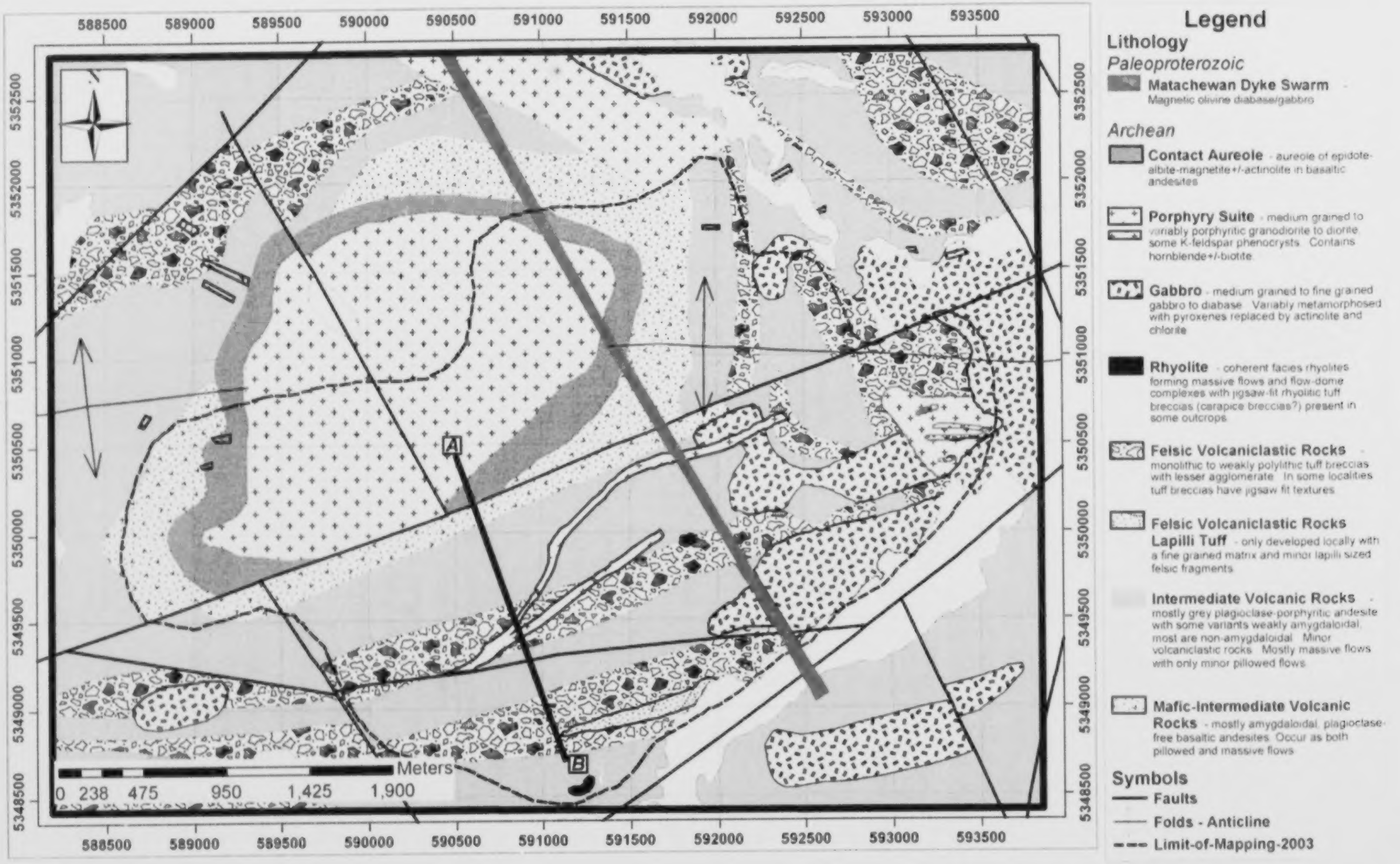
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Meters
Legend
Lithology
Paleoproterozoic
Matachewan Dyke Swarm - Magnetic olivine diabase/gabbro
Archean
Contact Aureole - aureole of epidote-albite-magnetite+/-actinolite in basaltic andesites
Porphyry Suite - medium grained to variably porphyritic granodiorite to diorite some K-feldspar phenocrysts. Contains hornblende+/-biotite
Gabbro - medium grained to fine grained gabbro to diabase. Variably metamorphosed with pyroxenes replaced by actinolite and chlorite
Rhyolite - coherent facies rhyolites forming massive flows and flow-dome complexes with jigsaw-fit rhyolitic tuff breccias (carapice breccias?) present in some outcrops
Felsic Volcaniclastic Rocks - monolithic to weakly polylithic tuff breccias with lesser agglomerate. In some localities tuff breccias have jigsaw fit textures
Felsic Volcaniclastic Rocks Lapilli Tuff - only developed locally with a fine grained matrix and minor lapilli sized felsic fragments
Intermediate Volcanic Rocks - mostly grey plagioclase-porphyritic andesite with some variants weakly amygdaloidal, most are non-amygdaloidal. Minor volcaniclastic rocks. Mostly massive flows with only minor pillowed flows
Mafic-Intermediate Volcanic Rocks - mostly amygdaloidal, plagioclase-free basaltic andesites. Occur as both pillowed and massive flows
Symbols
Faults
Folds - Anticline
Limit-of-Mapping-2003

Figure 44.1. Geological map of the Clifford stock and Blake River Group, Clifford Township. Geology inside of the limit of mapping 2003 is from this study, outside of this area is compiled *from* Jensen (1975). Line A–B is the line of section for the schematic section outlined in Figure 44.2.

euhedral. Conformably overlying the amygdaloidal basaltic andesite is a package of andesitic volcaniclastic rocks (*see* Figures 44.1 and 44.2). Péloquin and Piercey (2003) interpreted this package as andesitic flows, but recent investigations of drill core from Wallbridge Mining Company Ltd. illustrate that these rocks are actually andesitic tuffs, lapilli tuffs, and tuff breccias. These volcaniclastic rocks are matrix supported and consist mainly of fine-grained grey to grey-black andesitic tuff with varying amounts of feldspar lapilli and black andesitic fragments. Feldspar grains range from less than 1 to 5 mm in size and are euhedral to subhedral; in places they comprise 30 to 40% of the rock. Black andesitic fragments are not easily discernable on surface, but, in drill core, they are typically subrounded to subangular, range from less than 1 up to 10 cm in size and, in places, comprise 20 to 30% of the rock. Overlying this andesitic tuff unit is the first of two felsic volcaniclastic units consisting of a matrix-supported felsic tuff breccia (nomenclature from Fisher 1966)(*see* Figures 44.1 and 44.2). On surface, these tuff breccias appear monolithic to weakly polylithic; however, in drill core, these samples are clearly polylithic and contain clasts of andesite, basaltic-andesite, dacite, and rhyolite, and are angular to

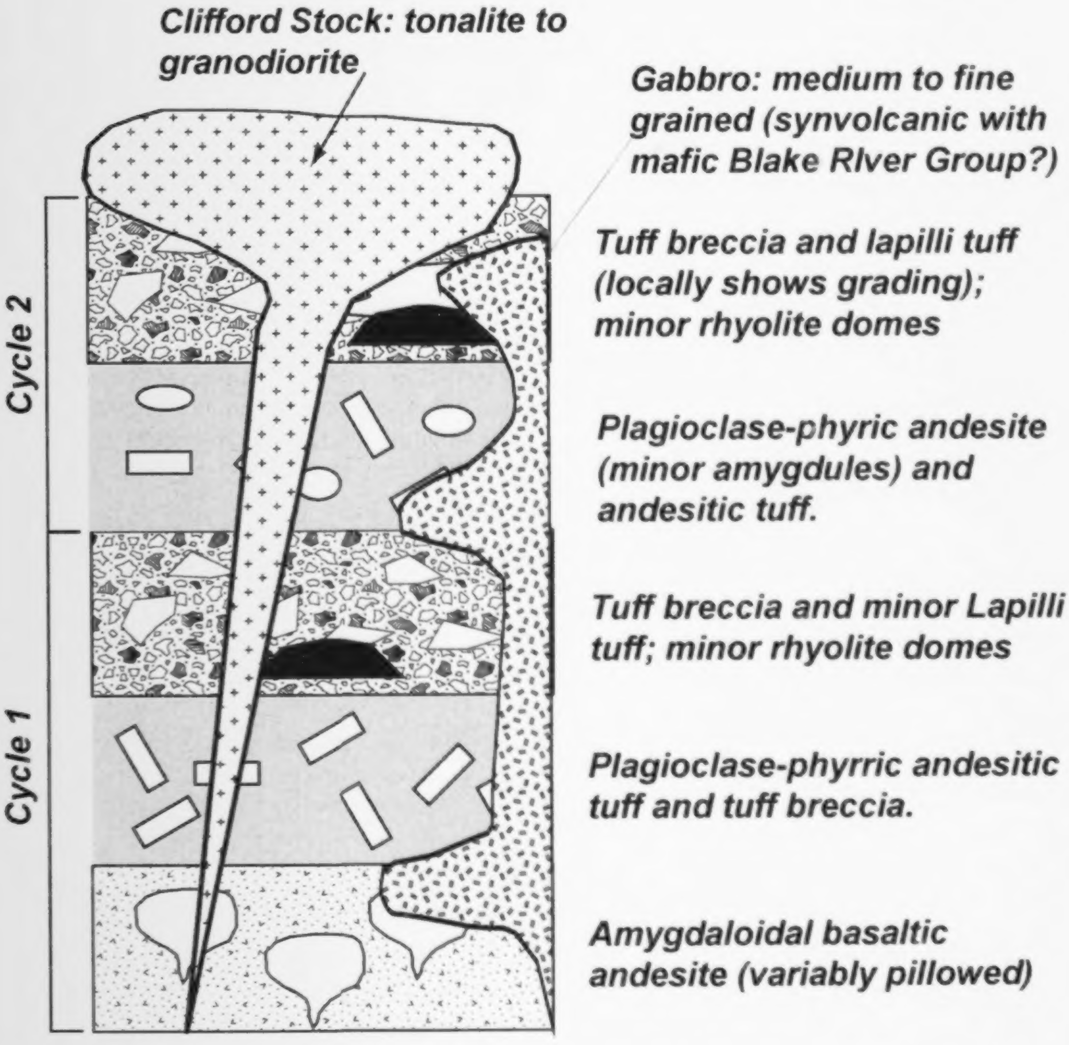

Clifford Stock: tonalite to granodiorite
Gabbro: medium to fine grained (synvolcanic with mafic Blake RIver Group?)
Tuff breccia and lapilli tuff (locally shows grading); minor rhyolite domes
Plagioclase-phyric andesite (minor amygdules) and andesitic tuff.
Tuff breccia and minor Lapilli tuff; minor rhyolite domes
Plagioclase-phyrric andesitic tuff and tuff breccia.
Amygdaloidal basaltic andesite (variably pillowed)
Cycle 2
Cycle 1

Figure 44.2. Schematic stratigraphic column for rocks of the Blake River Group in Clifford Township.

subrounded and range in size from 1 to 30 cm; all the clasts are within a matrix of fine siliceous ash material. Overlying the latter is a second unit of amygdaloidal and variably plagioclase porphyritic basaltic-andesite to andesitic tuff (*see* Figures 44.1 and 44.2) with small plagioclase feldspars less than 1 mm and up to 2 to 3 mm in size. The uppermost stratigraphic unit consists of a second tuff breccia to lapilli tuff (*see* Figures 44.1 and 44.2), very similar to the underlying tuff breccia, consisting of a matrix-supported breccia with angular clasts of predominantly dacite to rhyolite. There appears to be a southward younging of the tuff breccia into a lapilli tuff on a regional scale, suggesting normal grading outward from the Clifford stock (Jensen 1975).

Minor felsic flows and cryptodomes occur within the study area. In southern Clifford Township, there are felsic flows associated with a primarily felsic volcaniclastic package. These flows are white, aphyric rhyolitic rocks that are relatively massive in nature. In eastern Clifford Township, there are flow-banded rhyolitic volcaniclastic rocks spatially associated with synvolcanic rhyolitic dikes, interpreted to be part of a cryptodome (Photos 44.1a and 44.1b; *see* "U/Pb Geochronology"). The rhyolitic volcaniclastic rocks are different than most felsic volcaniclastic rocks in the area in that they are clast-supported, monolithic, and consist of polygonally jointed rhyolite fragments that have flow banding (Photo 44.1a). Rhyolitic intrusive rocks that intrude these felsic volcaniclastic rocks have irregular margins, are fine grained, and appear to be synvolcanic (*see* "U/Pb Geochronology"; Photo 44.1b).

The Blake River Group is intruded by the Clifford stock; east-northeast-trending dikes interpreted to be equivalent to the Clifford stock; Archean diabasic to gabbroic intrusive rocks; and gabbroic rocks of the Paleoproterozoic Matachewan dike swarm (*see* Figure 44.1). The Clifford stock is located in the core of the Blake River Group in Clifford Township and consists of a relatively equigranular tonalite to granodiorite, commonly hornblende bearing and locally hornblende-biotite bearing. The intrusion does not appear to be polyphase and contains xenoliths of the surrounding wall rock in only a few localities. Southeast of the Clifford stock numerous east- to northeast-striking dike- to sill-like intrusions cut the Blake River Group. These dikes are fine to medium grained, variably feldspar porphyritic, locally pyrite-bearing, siliceous, and dacitic to rhyolitic in composition; these dikes crosscut stratigraphy. Péloquin and Piercey (2003) interpreted the dikes to be synvolcanic; however, new stripped outcrops observed in 2004, coupled with U/Pb geochronology results (see below), suggest that they are not synvolcanic with the surrounding Blake River Group volcanic packages, but represent a distinctly younger magmatic event.

Mafic intrusive units cutting the Blake River Group stratigraphy are metamorphosed diabase to locally gabbro and are hard to distinguish from more mafic to intermediate volcanic rocks of the Blake River Group. These rocks may represent a subvolcanic feeder system to the basaltic-andesite to andesitic rocks of the Blake River Group. Also present are north-northwest-trending dikes of the 2.48 Ga Matachewan swarm. Unlike the Archean gabbro-diabasic rocks, these gabbroic dikes are coarse grained, have no recrystallization of primary igneous mineralogy, and are highly magnetic.

With the exception of the Matachewan swarm, the rocks of the Blake River Group, Archean diabase and gabbro, and Clifford stock (and equivalents) are interpreted to represent two cycles of volcanism and synvolcanic gabbro and diabase magmatism, followed by a younger felsic intrusive event (*see* Figure 44.2).

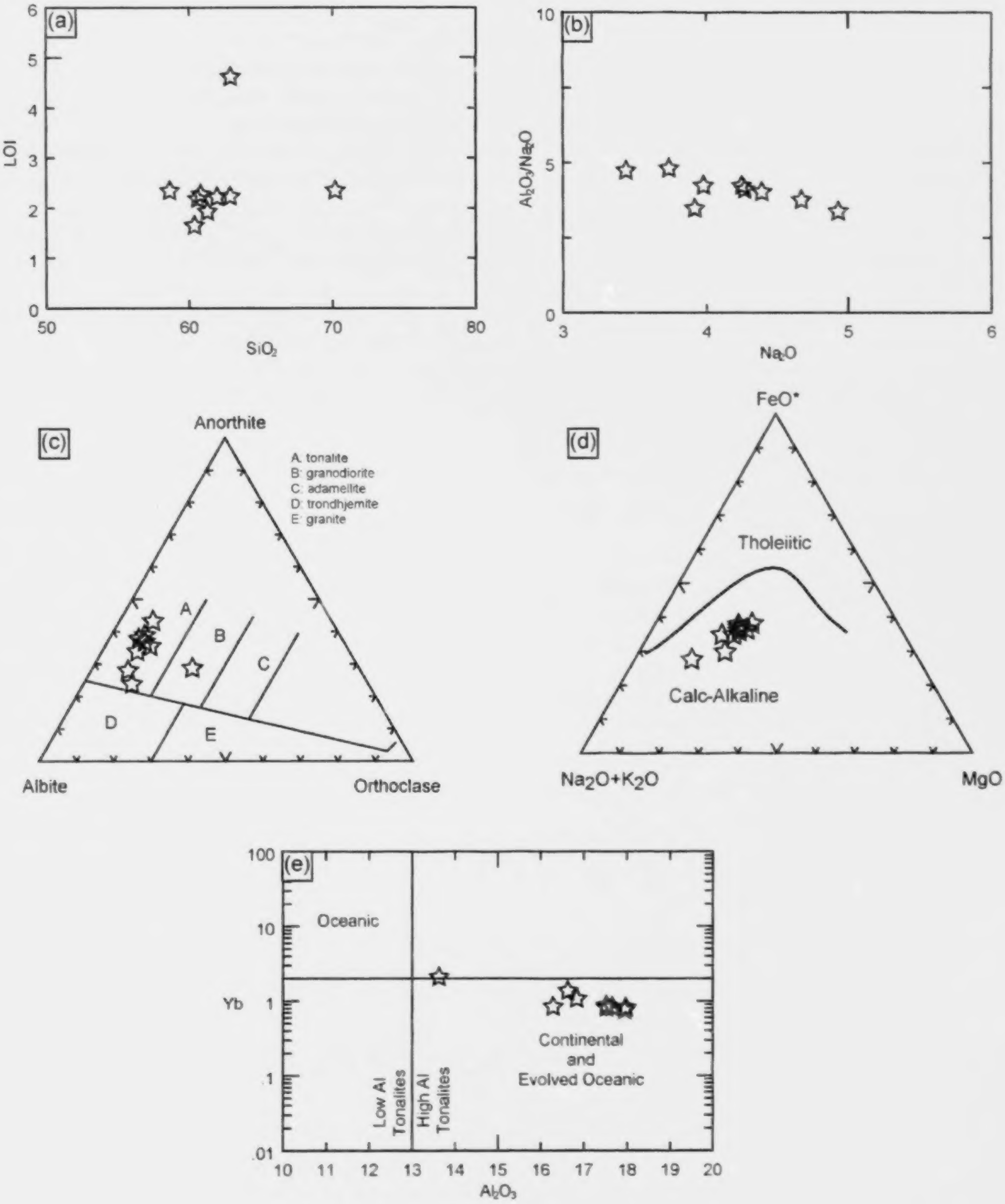


Figure 44.3. Geochemical plots for Clifford stock and related rocks: A) SiO$_2$ versus LOI; B) Al$_2$O$_3$/Na$_2$O versus Na$_2$O; C) normative feldspar abundance diagram (O'Connor 1965); D) AFM plot (Irvine and Baragar 1971); and (E) Al$_2$O$_3$ versus Yb diagram for tonalites (Arth 1979).

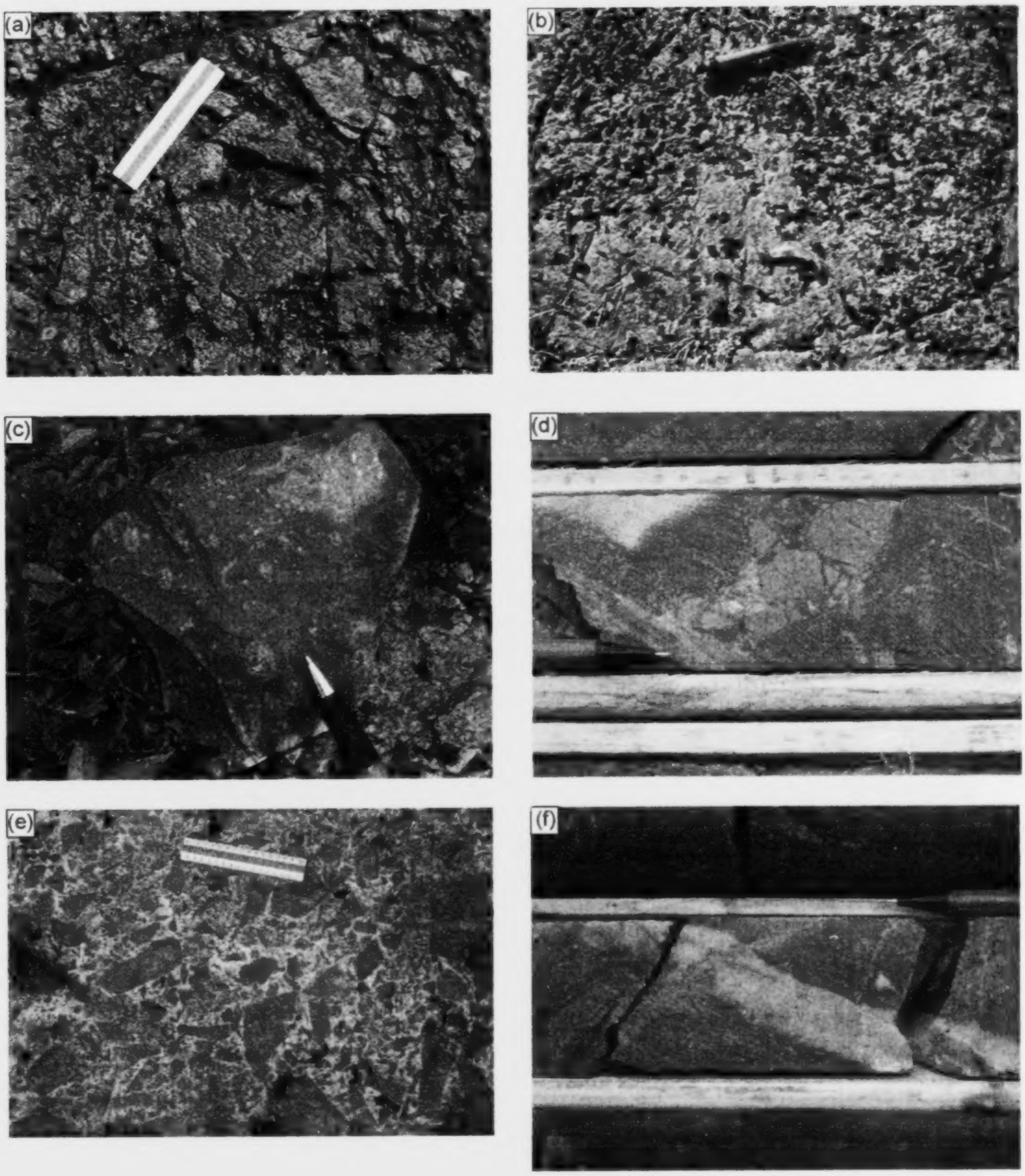


Photo 44.1. Photographs of rocks, alteration, and mineralization styles from Clifford Township. A) polygonally jointed and flow-banded rhyolite clasts within a clast-supported breccia interpreted to represent a carapace breccia to a rhyolite dome in eastern Clifford Township; B) synvolcanic rhyolite dike that intrudes into the carapace breccia. Note the irregular margins. This dike was dated as part of this study; C) amygdaloidal basaltic andesite with epidote-pyrite-quartz infillings of amygdules; D) silicified hyaloclastite on the edge of a pillowed basaltic-andesite with interstitial chalcopyrite, pyrite, quartz, and chlorite, typical of VMS-style mineralization; E) breccia-pipe occurrence from the Brett–Trethway–Croxall occurrence with brecciated rhyolite porphyry clasts with interstitial quartz (±sulphide); and F) veins of grey quartz with sulphide and flecks of fine-grained molybdenite typical of the later porphyry-style mineralization.

ALTERATION AND MINERALIZATION STYLES

Alteration and mineralization within Clifford Township includes 1) contact metamorphic alteration around the Clifford stock with minor pyrite mineralization; 2) VMS-style alteration and mineralization; and 3) intrusion-related or porphyry-style alteration and copper-molybdenum-gold (Cu-Mo-Au) mineralization.

Metamorphism-related alteration is dominated by low-grade regional prehnite-pumpellyite facies mineral assemblages (Hannington et al. 2003; Jensen 1975) and, in the immediate vicinity of the Clifford stock, contact metamorphism. Near the Clifford stock, a well-defined contact aureole surrounds the intrusion for 200 to 300 m (*see* Figure 44.1). In the aureole, the basaltic-andesitic to andesitic rocks exhibit a distinctive dark colouration and contain ubiquitous magnetite, lath-like needles of plagioclase (albite?), epidote patches and, in some cases, amphibole (actinolite?). Minor pyrite is present in the metamorphic aureole.

Volcanogenic massive sulphide (VMS)-style alteration is observed on surface and in drill core. In both surface and drill core, there is commonly amygdule filling by chlorite-quartz-epidote-pyrite assemblages in varying proportions, which is interpreted to represent semi-conformable-style alteration (e.g., Galley 1993). Most common are quartz-pyrite fillings, but there are also epidote-quartz-pyrite, chlorite-quartz and chlorite-pyrite infillings (Photo 44.1c). These mineral assemblages are also present in some rocks, commonly, the more mafic members of the Blake River Group, as patches, typically near permeable zones in the rocks (i.e., near hyaloclastite or in volcanic breccias). Silicification and chlorite alteration are present in some drill holes and are associated with sulphide mineralization and are interpreted to be more indicative of proximal, high-temperature alteration (e.g., Franklin 1993). This style of alteration and mineralization is present only in drill core and occurs associated with the lowermost basaltic-andesite pillow lava sequence. The mineralization is generally restricted to hyaloclastite along pillow margins. Along these margins, chalcopyrite, pyrite and quartz are found interstitial to angular hyaloclastite; sulphides comprise a maximum of approximately 10% of the rock (Photo 44.1d). Hyaloclastite fragments are either bleached to a white-pink colour and silicified or are completely chlorite altered with or without epidote. Finer grained ash-sized material in between the hyaloclastite is typically completely replaced by chlorite (*see* Photo 44.1d).

Porphyry Cu-Au-Mo-style alteration is present overprinting, and younger than, the VMS-style alteration. The porphyry-style alteration is present on both surface and drill core, and is associated with numerous breccia-pipe-style occurrences on surface (e.g., Brett–Trethway [also known as Croxall] prospect). On surface, the mineralization is not easily visible and occurs within breccia pipes, like the Croxall prospect. These pipes are broadly radial in nature and spatially associated with rhyolite porphyry and brecciated porphyry; in between the brecciated porphyry, there is abundant quartz±sulphide mineralization forming the interstices between porphyry clasts (*see* Photo 44.1e; E. Chaloux, unpublished data, 2004). Alteration associated with this style of mineralization is commonly silicification and pyrite alteration near the breccia pipes, whereas, outside of the breccia pipes, the regional wall rocks have a randomly oriented network of millimetre- to centimetre-scale quartz, epidote, potassium feldspar, hematite and calcite (±sericite) veins. In drill core, mineralization and alteration are associated primarily with a randomly oriented vein network that exhibits a complex paragenesis. The veinlets form a stockwork from 1 millimetre up to a few centimetres in width. The paragenesis seems to have formed, from oldest to youngest: 1) epidote, chlorite and sericite; 2) quartz-pyrite; 3) dark grey quartz-pyrite-chalcopyrite-molybdenum (and gold?; *see* Photo 44.1f); and 4) hematite-calcite±potassium feldspar. This paragenesis is not always present and some events appear to be synchronous and overlap in some drill holes. Nonetheless, there seems to be an intermediate Cu-Mo-Au event associated with dark grey quartz veins, and all alteration styles are cut by late hematite-calcite±potassium feldspar veins. The veins that host mineralization are widespread across all rock types, but are also hosted by dikes of rhyolitic feldspar porphyry similar to the Clifford stock; this suggests that this porphyry-style mineralization is a distinctly younger hydrothermal event in Clifford Township.

LITHOGEOCHEMISTRY

In this section, we present the preliminary results for the Clifford stock and associated dikes in Clifford Township. Samples were analyzed for major and trace elements at the OGS Geoscience Laboratories in Sudbury, Ontario. Major elements and LOI were determined by fused disc X-ray fluorescence (XRF). Precision was calculated for major elements using duplicate analyses and the Thompson–Howarth method (Fletcher 1981, 1986; Thompson and Howarth 1978) and is <5% for most major elements except MgO, which is 7%, and P_2O_5, which is 10%. These latter values are high because the MgO and P_2O_5 content of the duplicates are close to the limit of detection for XRF; precision for these elements is also likely <5% (O.M. Burnham and J. Schweyer, Geoscience Laboratories, personal communication, 2004). Accuracy for major elements, measured from replicate analyses of the GSD-11 felsic standard, is ±0–6% relative difference, except for Na_2O, which is 12% relative difference. The latter high value is due to Na_2O being close to the limit of detection in the GSD-11 standard; accuracy is approximately 3% for Na_2O by XRF at the OGS Geoscience Laboratories (J. Schweyer, Geoscience Laboratories, personal communication, 2004). Trace elements were analyzed via inductively coupled plasma mass spectrometry (ICP–MS: Nb, Ta, Zr, Hf, Y, Cs, Th, U, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and inductively coupled plasma atomic emission spectroscopy (ICP–AES: Ba, Be, Cd, Co, Cr, Cu, Li, Mo, Ni, S, Sc, Sr, V, W, Zn) using a closed-beaker multi-acid digestion prior to analysis (Burnham et al. 2002; Tomlinson, Bowins and Hechler 1998; Tomlinson et al. 1999). Niobium, Zr, and Y were also determined by pressed pellet XRF to determine whether the dissolutions for ICP–MS and ICP–AES analysis were complete: in most cases, Nb, Zr and Y determined by ICP–MS were within 10% of the values determined by XRF. Precision for ICP–AES methods using Thompson–Howarth analysis yielded the following values: Ba (5%), Be (5%), Cd (90%), Co (15%), Cr (15%), Cu (15%), Li (10%), Mo (not detected), Ni (10%), S (20%), Sc (10%), Sr (10%), V (10%), W (90%) and Zn (10%). Values that were imprecise, including Cd, Mo and W, are not considered reliable via this method and are not used in this paper. Accuracy for ICP–AES analyses based on replicate analysis of reference materials and is 0.3 to 4.2% relative difference (Lightfoot and Farrow 2002). Precision for ICP–MS analysis using Thompson–Howarth analysis yielded the following values: Nb (5%), Ta (5%), Zr (10%), Hf (10%), Y (10%), Cs (10%), Th (7%), U (7%), and REE (<10 to 12%). Accuracy for ICP–MS analyses based on replicate analysis of reference materials are <8% relative difference (%RD) for all elements except Nb (9.8%RD) and Pr (12.3%RD) (Lightfoot and Farrow 2002).

Preliminary results for the geochemistry of the Clifford stock and associated rocks are shown in Figures 44.3 and 44.4. The Clifford stock and associated rocks have SiO_2 values that are ~60%, for the most part, LOI values <3%, and Al_2O_3/Na_2O (*see* Spitz and Darling 1978) values of <5 (Figures 44.3a and 44.3b); this suggests that the rocks are relatively fresh and have intermediate to felsic compositions. The normative mineralogy for the rocks suggest that the bulk of the Clifford stock and associated rocks have tonalitic compositions (Figure 44.3c), are subalkaline (Nb/Y <0.7), and follow a transitional fractionation trend (Figure 44.3d). The rocks have Al_2O_3 > 13% and have Yb ≤2 ppm suggesting that they are high-Al tonalites that have either a continental affinity, or are fractionated oceanic tonalites (Figure 44.3e). Primitive mantle-normalized plots for the Clifford stock and related rocks are steep with light rare-earth element (LREE)-enrichment, and heavy rare-earth element (HREE)-depletion, negative Nb, Ti and, to a lesser extent, Eu anomalies, positive Zr and Hf anomalies, and overall depletions in compatible elements (Figure 44.4a). The rare-earth element signatures of the rocks, relative to upper continental crust, are relative flat to weakly LREE-depleted, with positive Eu anomalies (Figure 44.4b); these features suggest accumulation of plagioclase coupled with interaction, or derivation from, upper-continental crust-like material. Increasing interaction with crust is also supported by other trace element features of the data. For example, the Nb/Th ratios of the rocks decrease with increasing SiO_2, reflecting increased Th and SiO_2 due to crustal assimilation (Figure 44.4c). The Nb/Th ratios also decrease with decreasing Nb/Ta values and form an array that ranges from near crustal values (Nb/Th_{UCN} ~1, Nb/Ta ~12) towards chondritic values (e.g., Barth et al. 2000; McLennan 2001; Rudnick et al. 2000; Figure 44.4d), consistent with mixing between more mantle-derived material and crustal material.

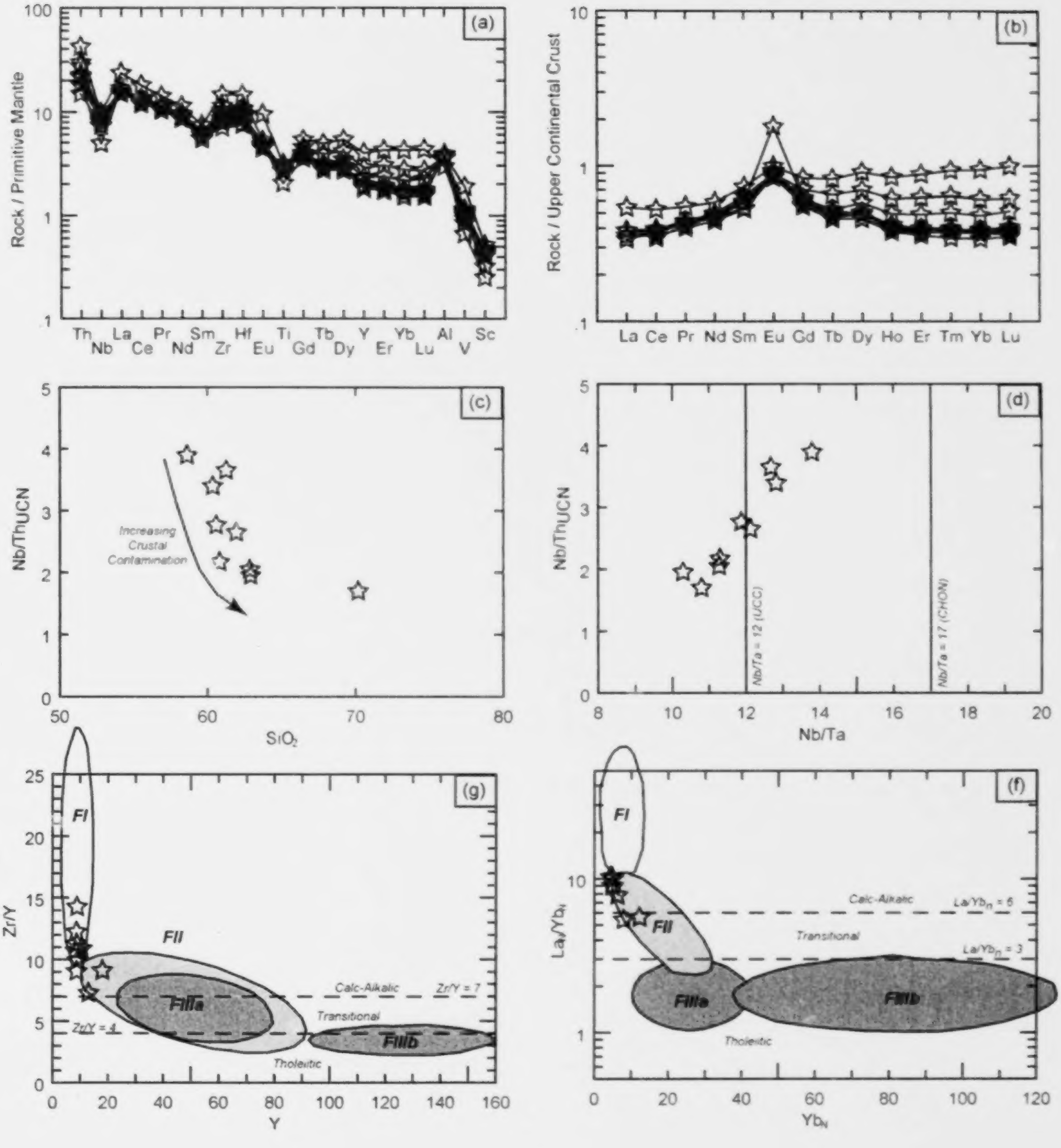
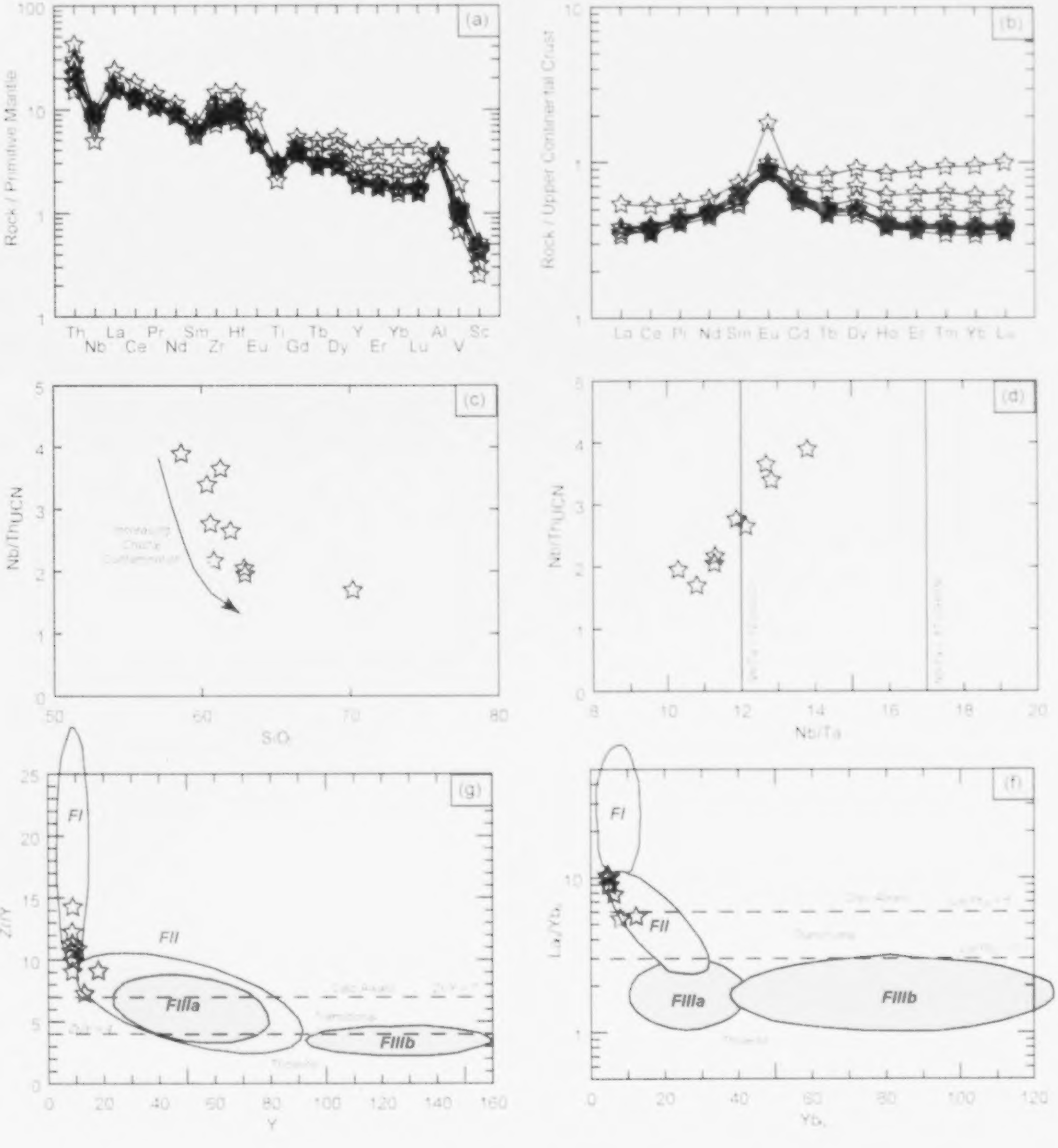


Figure 44.4. Trace element geochemical plots for the Clifford stock and related rocks. Primitive mantle normalized plots (values from Sun and McDonough 1989)for the Clifford stock and related rocks have broadly calc-alkalic signatures (A). The upper-crust normalized plots (values *from* McLennan 2001) for the Clifford stock and equivalents (B), coupled with their Nb/Th$_{UCN}$–SiO$_2$ (C) and Nb/Ta–Nb/Th$_{UCN}$ (D) systematics (UCN = upper crust normalized) are consistent with crust-mantle mixing and some interaction with crustal material. UCC = upper continental crust, CHON = chondrite; Nb/Ta values for reservoirs *from* Barth, McDonough and Rudnick (2000) and Rudnick et al. (2000). The Zr/Y–Y and La/Yb$_n$–Yb$_n$ values are consistent with the Clifford stock and equivalents having FI to FII affinities (G–F); diagrams *from* Lesher et al. (1986).



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The Zr/Y versus Y and La/Yb$_n$ versus Yb$_n$ systematics of the Clifford stock and related rocks are shown in Figure 44.4. These diagrams were created by Lesher et al. (1986) as a means of potentially discriminating between most prospective (FIIIa, FIIIb), moderately prospective (FII), and least prospective (FI) VMS environments. Notably, in these diagrams, the rocks from the Clifford stock and equivalents have low Y and Yb$_n$, and high Zr/Y and La/Yb$_n$ values, consistent with an FII to FI designation (Figures 44.4e and 44.4f). Given these constraints, this type of pluton would not necessarily be a highly prospective VMS-related subvolcanic intrusion. Nonetheless, the ages, and porphyry Cu-Mo-Au-style mineralization associated with this pluton suggests that this intrusion likely represents a post-Blake River intrusion and may have porphyry Cu-Mo-Au potential.

U/Pb GEOCHRONOLOGY: PRELIMINARY RESULTS

Preliminary geochronological results from Clifford Township include a sample from the Clifford stock, a dike interpreted to be related to the Clifford stock, and a rhyolite intrusive interpreted to be a synvolcanic cryptodome within the Blake River Group. Samples were analyzed at the Jack Satterly Geochronology Laboratory at the University of Toronto following the methods of Davis and Lin (2003).

Age of Clifford Stock

This sample (03SJP-115, Universal Transverse Mercator (UTM) North American Datum 1983 (NAD83), Zone 17, 591133E, 5351000N) was taken from the Clifford stock to test the age of the Clifford stock to compare to ages for the Blake River Group and ages for other subvolcanic intrusive rocks within the Blake River Group. This sample is a tonalite to granodiorite, is equigranular to weakly porphyritic with some larger 0.5 cm potassium feldspar phenocrysts and/or megacrysts, hornblende is the dominant mafic phase and there are some rounded epidote patches within the sample. A preliminary age of 2686.9±1.2 Ma has been obtained for this sample. This age is interpreted to represent the magmatic age of the Clifford stock and is similar to the Clarice Lake pluton (Corfu and Noble 1992), Lac Dufault (Mortensen 1993, and references therein) and gold-related intrusive rocks in the Porcupine Camp (Corfu et al. 1989).

Age of Felsic Dikes

This sample (03SJP-059-1, UTM NAD83, Zone 17, 590369E, 5349181N) is from a dike intruding andesitic volcaniclastic rocks and was initially interpreted to be synvolcanic with the surrounding andesites. Further examination of stripped outcrops in 2004 illustrates that the dikes have straight margins and are not synvolcanic with the surrounding Blake River Group rocks. Furthermore, in drill core, the porphyry dikes, interpreted to be the same as those sampled, exhibit razor-sharp contacts with surrounding rocks further adding evidence for a post-volcanic origin. A preliminary age of 2688.6±2.6 Ma has been obtained for this sample. This age is similar to the Clifford stock and suggest they are coeval with this stock.

Blake River Group Magmatism

This sample (03ASP-0130-1.2, UTM NAD83, Zone 17, 593407E, 5350603N) was taken of a porphyritic rhyolite plug, possibly a dome, characterized by alternating massive lava and thin layers of rhyolite breccia. This assemblage was interpreted by Jensen (1975) as being a synvolcanic intrusion. The interlayering of massive lava and breccia leads us to conclude that the assemblage is, at least in part, extrusive in nature. The rhyolitic breccias are mostly clast-supported, highly angular and polygonally jointed fragments with flow banding (*see* Photo 44.1a). The contacts between the massive lavas and the breccias are irregular and amoeboidal. The rhyolite assemblage is interpreted to be a cryptodome formed by intrusion of synvolcanic rhyolite dikes and/or sills within a pre-existing volcaniclastic pile. A preliminary age of 2695.6±2.1 Ma has been obtained on this sample.

DISCUSSION AND SUMMARY

The new U/Pb age determinations, contrasting mineralization styles, and lithogeochemistry suggest a complex and episodic magmatic–hydrothermal history for the rocks of Clifford Township. The first events to occur in this region are magmatism and hydrothermal mineralization associated with the Blake River Group. The preliminary age obtained for the Blake River Group in this paper, 2695.6±2.1 Ma, overlaps, within error, existing ages for the Blake River Group in both Ontario and Québec (Ayer et al. 2002, and references therein; Corfu and Noble 1992; Mortensen 1993), and extends the age range for the Blake River Group to 2701 to 2696 Ma. The Blake River Group in Québec has been interpreted to represent a volcanic arc to back-arc setting (Lafleche, Dupuy and Dostal 1992; Péloquin 1999), and given the similarity of ages and some similarities in volcanic styles (Péloquin and Piercey 2003), it is likely that the Blake River Group in Ontario represents a continuation of this arc–back-arc system. Furthermore, the occurrence of VMS-related hydrothermal alteration and mineralization in Clifford Township, and the multitude of such style of mineralization in Québec, suggests that the VMS-style hydrothermal activity in Clifford Township likely represents a circa 2700 to 2696 Ma hydrothermal event.

The Clifford stock and associated dikes were originally considered to be a subvolcanic intrusive complex of Blake River Group age that potentially drove VMS-related hydrothermal alteration and mineralization in Ben Nevis and Clifford townships (Hannington et al. 2003). The geochronological results presented herein clearly show that this even represents a younger transitional to calc-alkalic magmatic event that involved interaction with continental crust, be that via assimilation of material enroute to the surface, or via sediment melting on the subducted slab. The ages for this magmatic activity are similar to other magmatic rocks that intrude the Blake River Group, including the Clarice Lake pluton (2689±1 Ma: Corfu and Noble 1992) and the Lac Dufault pluton (circa 2690 Ma: Galley and van Breeman 2002 and references therein). The occurrence of porphyry Cu-Mo-Au-style mineralization within these late porphyry-related rocks suggests that this mineralization event is synchronous with the Clifford stock (our preferred interpretation), or younger than the Clifford stock and younger than 2687 to 2689 Ma. Nevertheless, this magmatic–hydrothermal event is clearly younger than the earlier VMS-related event.

Similar early VMS-style and later, overprinting porphyry-style mineralization events have been observed in other VMS camps, such as Sturgeon Lake (Galley, van Breeman and Franklin 2000) and Noranda (Galley and van Breeman 2002). In the Noranda camp, later, crosscutting, intrusion-related porphyry Cu-Mo-Au occurrences are circa 2697 Ma in age (Galley and van Breeman 2002), only slightly younger than the volcanic-hosted VMS-style mineralization (2701 to 2698 Ma: Mortensen 1993). The results of this study extend the ages of porphyry Cu-Mo-Au mineralization to circa 2690 Ma and suggest that there were multiple pulses of overprinting porphyry-style mineralization in the Blake River Group. The implications of this are interesting as it suggests that other younger plutons in the Blake River Group, like the Lake Clarice and Lac Dufault plutons, may have potential to host porphyry Cu-Mo-Au mineralization. It remains to be seen, however, whether any of these plutons will yield economic concentrations of this style of mineralization.

ACKNOWLEDGMENTS

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45. Discover Abitibi. Metamorphic Subproject. Metamorphic Zones and Gold Exploration Targets East of Timmins: Interim Report

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INTRODUCTION

This report summarizes ongoing results of a project designed to upgrade the metamorphic framework for gold exploration in the Timmins–Kirkland Lake area, Abitibi greenstone belt. Metamorphic data and concepts used to explain the origin and evolution of metamorphic rocks contribute to the reconstruction of the geological setting of gold deposits and provide key constraints on the nature, timing, duration and distribution of gold mineralization and related hydrothermal alteration. In this way, metamorphic tools advance knowledge of known deposits and help to define new exploration targets.

The new metamorphic map (approximately 3000 km^2) of the region east of Timmins (Thompson 2004) is based on regional petrography of thin sections obtained from the Ontario Geological Survey (522), Porcupine Joint Venture (56), and from samples collected for the current project (103). Mineral assemblages and textures in seven associations of metamorphosed plutonic, volcanic, and sedimentary rocks and one comprising unmetamorphosed granitoids outline metamorphic zone boundaries that have the potential to host gold (Hall 1998; Mikucki and Roberts 2004; Thompson 2002, 2003a, 2003b, 2004). Mapped on the surface and at depth in the Dome and Paymaster mines, metamorphic zones are of interest at the regional scale across the greenstone belt and in more detail where they outline kilometre-scale metamorphic "hot" and "cold" spots.

ROCK ASSOCIATIONS AND METAMORPHIC GRADE

The thin sections examined were classified with respect to metamorphic grade and rock associations (Table 45.1) and converted to a point data distribution in ESRI® ArcMap™ (ArcGIS® 8.3). Metamorphic zone boundaries (Figure 45.1) are derived from the point data. To avoid clutter, individual symbols representing rock association and grade for each thin section are omitted from this version of the metamorphic map. The sequence and spacing of zones are derived mainly from the distribution of metamorphic grade in mafic and quartzofeldspathic rocks and, locally, by mineralogical changes in ultramafic, aluminous, and carbonate-rich rocks as well as chemical metasedimentary rocks such as iron formation. Documentation of metamorphic grade in a range of compositions insures that some measure of metamorphic grade is determined for most parts of the project area. Dependent on data density, control on the location of zone boundaries ranges from excellent to poor.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.45-1 to 45-12.

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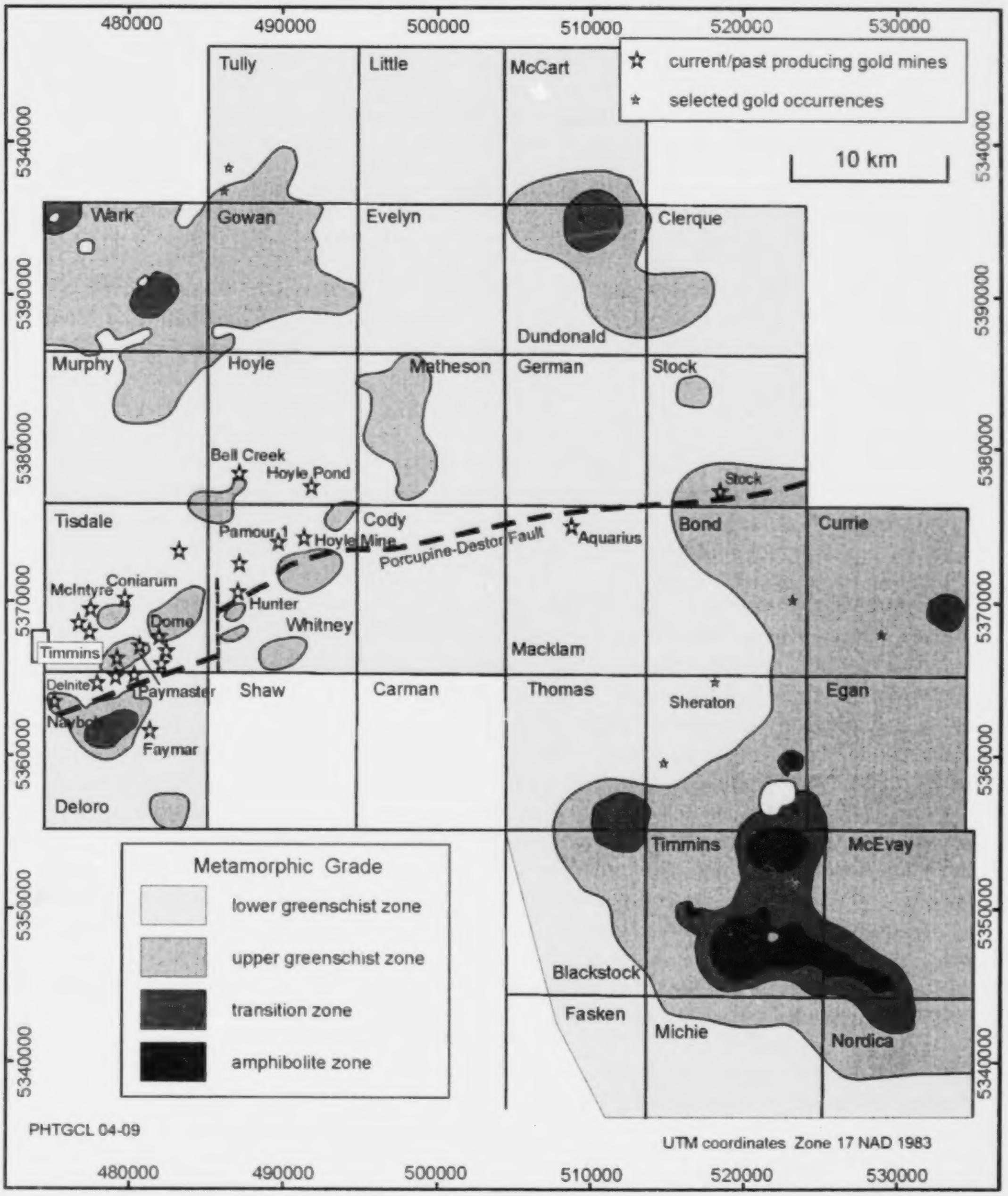
Metamorphic zones are descriptive, mappable features defined by mineral assemblages in particular rock compositions. Determined by mineral assemblages in a variety of rock compositions, metamorphic facies represent particular ranges of temperature and pressure. Greenschist (lower and upper) and amphibolite zones correspond approximately to the greenschist and amphibolite facies, respectively (*see* Table 45.1; *see* Figure 45.1). The intervening facies boundary occurs within the transition zone. A feature of metamorphosed basalt and gabbro, the transition zone typically contains mineral assemblages

Table 45.1. Metamorphic zones on the map are defined on the basis of variations in diagnostic mineral assemblages (point data) in one or more rock associations. The first digit of the two-digit number in each cell of the table indicates the rock association. The second digit indicates the relative metamorphic grade for the rock association (higher number, higher grade). The relative positions of the boundaries in rock associations 2 to 7 that are used to subdivide the greenschist zone are inferred from the current data set. The precise positions have yet to be calibrated. Mineral name abbreviations: ab - albite, act - actinolite, am - amphibole undifferentiated, and - andalusite, bt - biotite, cb - carbonate (ankerite, calcite, dolomite, magnesite, siderite), cht - chlorite, crd - cordierite, ctd - chloritoid, cum - cummingtonite, diop - diopside, epg - epidote group, grt - garnet, gru - grünerite, hn - hornblende, kf - potassium-feldspar, mt - magnetite, plg - plagioclase, se - serpentine, sil - sillimanite, st - staurolite, tlc - talc, trm - tremolite, wm - white mica (muscovite, paragonite, talc).

Rock Association	**Metamorphic Grade**			
	Greenschist Facies		**Amphibolite Facies**	
	Metamorphic Zones on Map			
	Lower Greenschist Zone	**Upper Greenschist Zone**	**Transition Zone**	**Amphibolite Zone**
	Diagnostic Mineral Assemblages			
1) Metabasites: metabasalt/gabbro, greenstone, amphibolite, metadiabase	11 act-cht-epg-ab		12 act-hn	13 hn-plg(calcic)
2) Metaquartzofeldspathic rocks: metarhyolite/dacite, qtz-fp metaporphyry, felsic volcaniclasite, metawacke	21 cht-wm cht-kf	22 biotite		
3) Metamorphosed ultramafic rocks: metakomatiite, metaperidotite/dunite	31 cht-tlc-cb cht-tlc-se	32 clinoamphibole (trm, cum)		
4) Metamorphosed aluminum-rich rocks: metashale/siltstone, meta-hydrothermal alteration	41 cht-wm	42 bt, bt-grt, ctd-cht	43 crd-and/sil-bt st-and/sil-bt, crd orthoamphibole	
5) Metamorphosed iron formation: chemical metasedimentary rocks	51 qtz-cht cht-cb, mt-qtz	52 clinoamphibole (cum/gru), am-grt, two am		
6) Metamorphosed granitoids: metagranite to metatonalite, metadiorite	61 cht-kf cht-wm	62 biotite, bt-epg, bt-epg-am		
7) Metamorphosed carbonate-rich rocks: carbonate metasediments, meta-interpillow rock, meta-hydrothermal alteration, cht-cb schist	71 cht-cb-qtz cht-cb-wm-qtz	72 bt-cht-cb epg-cht-am-cb	73 diop-am-grt, hn-bt-qtz	
8) Unmetamorphosed granitoids: granite to tonalite	80 no metamorphic minerals			
	Greenschist Facies		**Amphibolite Facies**	

with characteristics of both the upper greenschist and amphibolite zones. Given the wide distribution and predominance of greenschist-facies metamorphism in the project area (Jolly 1978), subdivision of the greenschist zone using the appearance of biotite in muscovite- and potassium feldspar-chlorite-bearing quartzofeldspathic and carbonate-rich rocks and the appearance of amphibole in ultramafic rocks is a useful addition to the metamorphic tools available for gold exploration in the Abitibi greenstone belt.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☆ current/past producing gold mines
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10 km
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McCart
Wark
Gowan
Evelyn
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Dundonald
Murphy
Hoyle
Matheson
German
Stock
Bell Creek
Hoyle Pond
Stock
Tisdale
Cody
Bond
Currie
Pamour 1
Hoyle
Mine
Porcupine-Destor Fault
Aquarius
McIntyre
Coniarum
Hunter
Whitney
Dome
Timmins
Macklam
Delnite
Paymaster
Shaw
Carman
Thomas
Sheraton
Egan
Naybob
Faymar
Deloro
Timmins
McEvay
Metamorphic Grade
lower greenschist zone
upper greenschist zone
transition zone
amphibolite zone
Blackstock
Fasken
Michie
Nordica
PHTGCL 04-09
UTM coordinates Zone 17 NAD 1983

Figure 45.1. Simplified metamorphic map of the Timmins East map area. Point data omitted here for clarity will be included on final metamorphic map of complete project area.

with characteristics of both the upper greenschist and amphibolite zones. Given the wide distribution and predominance of greenschist-facies metamorphism in the project area (Jolly 1978), subdivision of the greenschist zone using the appearance of biotite in muscovite- and potassium feldspar-chlorite-bearing quartzofeldspathic and carbonate-rich rocks and the appearance of amphibole in ultramafic rocks is a useful addition to the metamorphic tools available for gold exploration in the Abitibi greenstone belt.

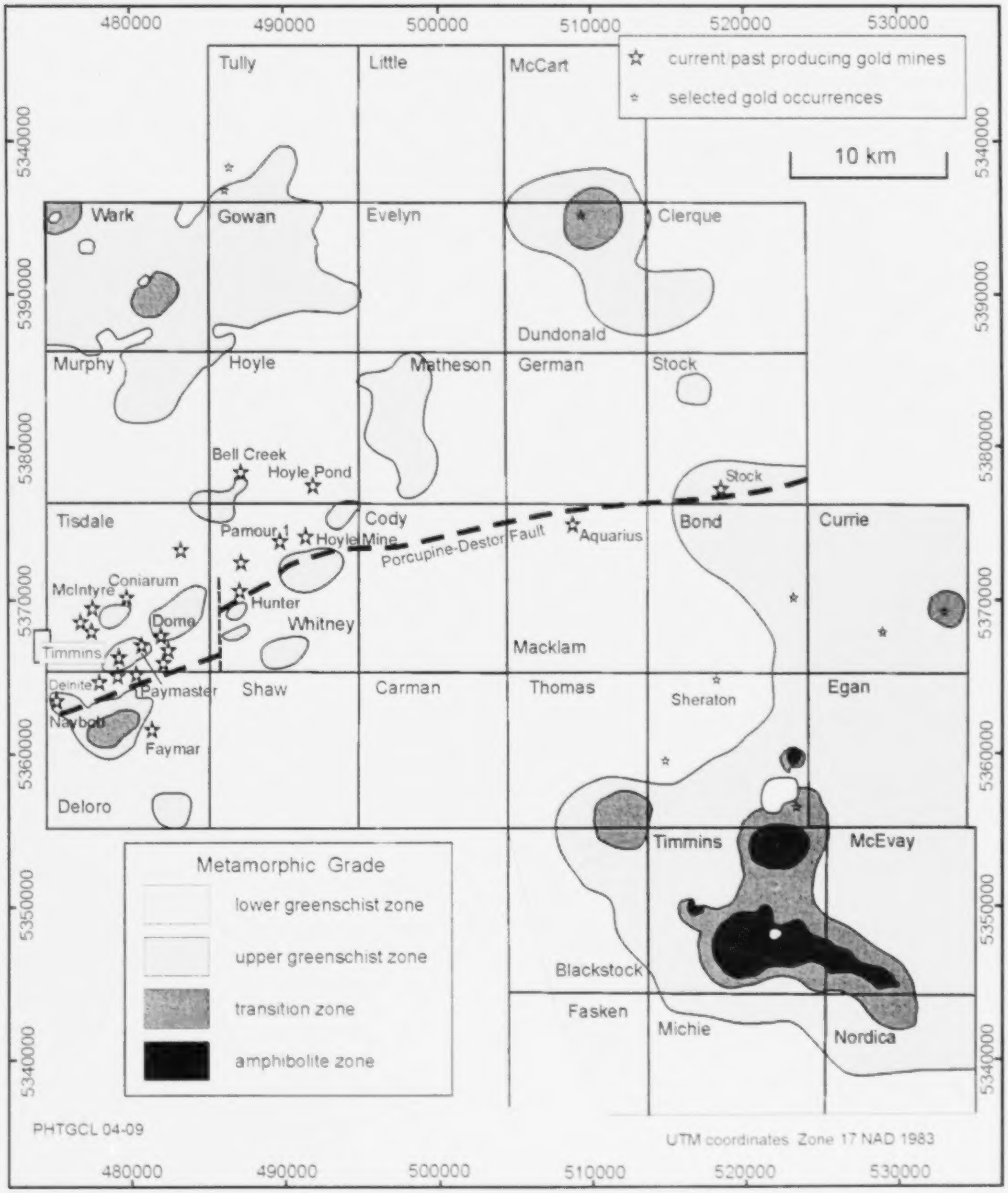
current/past producing gold mines
selected gold occurrences
10 km
Tully
Little
McCart
Wark
Gowan
Evelyn
Clerque
Dundonald
Murphy
Hoyle
Matheson
German
Stock
Bell Creek
Hoyle Pond
Stock
Tisdale
Cody
Bond
Currie
Pamour 1
Hoyle
Mine
Porcupine-Destor Fault
Aquarius
McIntyre
Coniarum
Hunter
Dome
Whitney
Timmins
Macklam
Delnite
Paymaster
Shaw
Carman
Thomas
Egan
Sheraton
Naybob
Faymar
Deloro
Timmins
McEvay
Blackstock
Fasken
Michie
Nordica
Metamorphic Grade
lower greenschist zone
upper greenschist zone
transition zone
amphibolite zone
PHTGCL 04-09
UTM coordinates Zone 17 NAD 1983
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Figure 45.1. Simplified metamorphic map of the Timmins East map area. Point data omitted here for clarity will be included on final metamorphic map of complete project area.

TIMMINS EAST METAMORPHIC MAP AND GOLD MINERALIZATION

A part of the much larger metamorphic map of the Timmins–Kirkland Lake project area, the Timmins East metamorphic map (*see* Figure 45.1) is typical in that it contains relatively high-grade metamorphic zones tens of kilometres wide and much smaller metamorphic anomalies where metamorphic grade is either higher ("hot spot") or lower ("cold spot") than the surrounding regional metamorphic zone. The lower greenschist, upper greenschist, transition and amphibolite zones represent a range of metamorphic grade that corresponds to pressures and temperatures characteristic of the greenschist and amphibolite facies (350 to 600°C, 2.5 to 4.0 kilobars; Powell, Carmichael and Hodgson 1993; Thompson 2002). Foliations and lineations defined by metamorphic minerals indicate that metamorphism overlapped in time and space with the main phases of ductile deformation. At the present erosion level (Ayer and Trowell 1998; Ayer, Berger and Trowell 1999), the volume of granitoids is small and concentrated mainly in the southeast part of the area (*see* Figure 45.1). Petrographic evidence there (Vaillancourt 2001; Thompson 2003b) and west of Timmins (Thompson 2002) is consistent with intrusion of plutonic rocks before (synvolcanic), during and after regional metamorphism.

The source of heat for regional metamorphism remains a controversial subject. Given the limited distribution and age range of granitoid rocks at the present erosion level, plutonic magmatism is not a likely source of the heat required to form the metamorphic zones across most of the map area. The combination of heat inherited from thinning the lithosphere at the time of volcanism and/or sedimentation and radiogenic heat produced by thicker than normal crust during subsequent crustal orogenesis (Thompson, 1989a, 1989b; 2003b, in press) is the heat source for regional metamorphism preferred here. Within this context, however, intrusive granitoids associated with volcanism and with the later stages of orogenesis did produce relatively localized contact metamorphic aureoles. For example, integration of metamorphic data with the geology mapped by Vaillancourt (2001) led to the suggestion (Thompson 2003b) that the highest grade rocks in the southeast part of the area (*see* Figure 45.1) are contact effects of the intrusion of pre-and post-metamorphic granitoids.

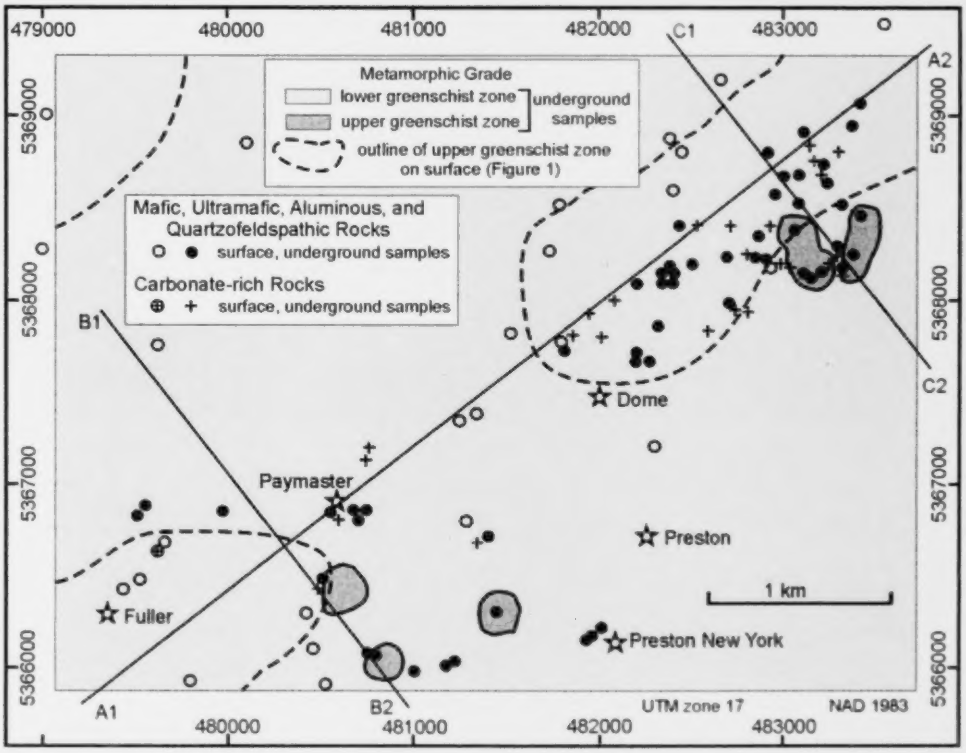
Over most of the map area, maximum metamorphic grade is represented by small areas of the transition zone which overlaps the boundary between the greenschist and amphibolite facies (*see* Table 45.1). Only in the southeast corner where intrusive granitoids are prominent is the highest grade amphibolite zone present. In addition to the boot-shaped transition zone associated with amphibolite zone rocks in the southeast corner, there are six occurrences of transition zone metamorphic rocks (*see* Table 45.1; *see* Figure 45.1). In Thomas, Deloro and Wark (northwest) townships, the higher grade zones occur on or near small (<2 km) plutons that appear on geological maps (Ayer and Trowell 1998; Ayer, Berger and Trowell 1999). According to these studies, there are no exposed granitoids close to the transition zone "hot spots" located in Currie, Dundonald and Wark (southeast) townships. Two of the latter are associated with gold occurrences (*see* Figure 45.1). There is also a gold occurrence in the transition zone near the top of the "boot".

Upper greenschist zone metamorphic rocks (*see* Table 45.1) occur as patches tens of kilometres wide that surround higher grade zones and as numerous small "hot spots" within the more extensive lower greenschist zone (*see* Figure 45.1). The distinctive spotted pattern of small anomalies east and northeast of Timmins overlaps a concentration of significant gold mines. Eight of these mines are close to the upper–lower greenschist zone boundary. The Stock mine near the east edge of the map may be as well. There are gaps of 3 to 10 km between data points at the mine and those to the north and west. In the northwest corner of the map (Tully Township), two gold occurrences bracket the upper–lower greenschist zone boundary.

The lower greenschist zone (*see* Table 45.1; *see* Figure 45.1) is the most extensive in the map area. In addition, small isolated patches of the zone ("cold spots") occur within higher grade zones in the northwest and southeast. Too small to show on the map in this report, there is a lower greenschist zone anomaly associated with the amphibolite zone "hot spot" located on the "spur" near the heel of the boot-shaped higher grade zone and with the hot spot immediately north of the boot. The somewhat larger lower greenschist zone anomaly in the southeast corner of Sheraton Township is the only "cold spot" associated with a gold occurrence. A number of current and past producing gold mines occur within the lower greenschist zone at some distance from the boundary with the upper greenschist zone. In these cases, gold mineralization may be older or younger than the metamorphic zones.

THE THIRD DIMENSION

With the support of A. Still and E. Barr (Porcupine Joint Venture), an attempt was made to explore in more detail the upper greenschist zone metamorphic anomaly that was found to be associated with the Dome Mine by an earlier pilot study (Thompson 2002). Additional sampling improved control on the boundaries of the upper greenschist zone on the surface and outlined its extension to depths of 2000 m (Figures 45.2 and 45.3). The new data also outlined a new metamorphic anomaly to the southeast that overlies the Fuller past-producing mine and may extend downward to 2000 m in the Paymaster Mine. The data compiled for this preliminary three-dimensional interpretation seems to indicate that the anomaly at the Dome Mine forms a narrow pipe-like body with a diameter much less than that of the surface anomaly (*see* Figure 45.2 and 45.3). However, the limited distribution of the data does not


479000
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C1
A2
5369000
5368000
5367000
5366000
Metamorphic Grade
lower greenschist zone
upper greenschist zone
underground samples
outline of upper greenschist zone on surface (Figure 1)
Mafic, Ultramafic, Aluminous, and Quartzofeldspathic Rocks
○ ● surface, underground samples
Carbonate-rich Rocks
⊕ + surface, underground samples
B1
C2
Dome
Paymaster
Preston
1 km
Fuller
Preston New York
A1
B2
UTM zone 17
NAD 1983

Figure 45.2. Metamorphic map of the area in vicinity of the Dome and Paymaster mines. See Figure 45.3 for profiles A_1–A_2, B_1–B_2, and C_1–C_2. Underground samples and inferred upper greenschist zone metamorphic anomalies projected to the surface along vertical lines.

preclude the presence of more than one pipe-like source for the surface anomalies. This preliminary study indicates that at the Dome Mine, and possibly at the Paymaster Mine, the surface anomaly narrows with depth in the crust. This geometry is consistent with limited petrography completed in the course of structural studies at the Paymaster Mine (D. Rhys, Panterra Geoservices Inc., personal communication, 2004). That is to say, metamorphic zoning in the third dimension is as irregular as it is on the surface. At least to depths of 2000 m, the increase in grade does not outline a simple thermal dome. More detailed work confirms the spatial relation between the Dome Mine and an upper greenschist zone metamorphic anomaly and supports the working hypothesis that metamorphic anomalies are prospective hosts for gold mineralization.

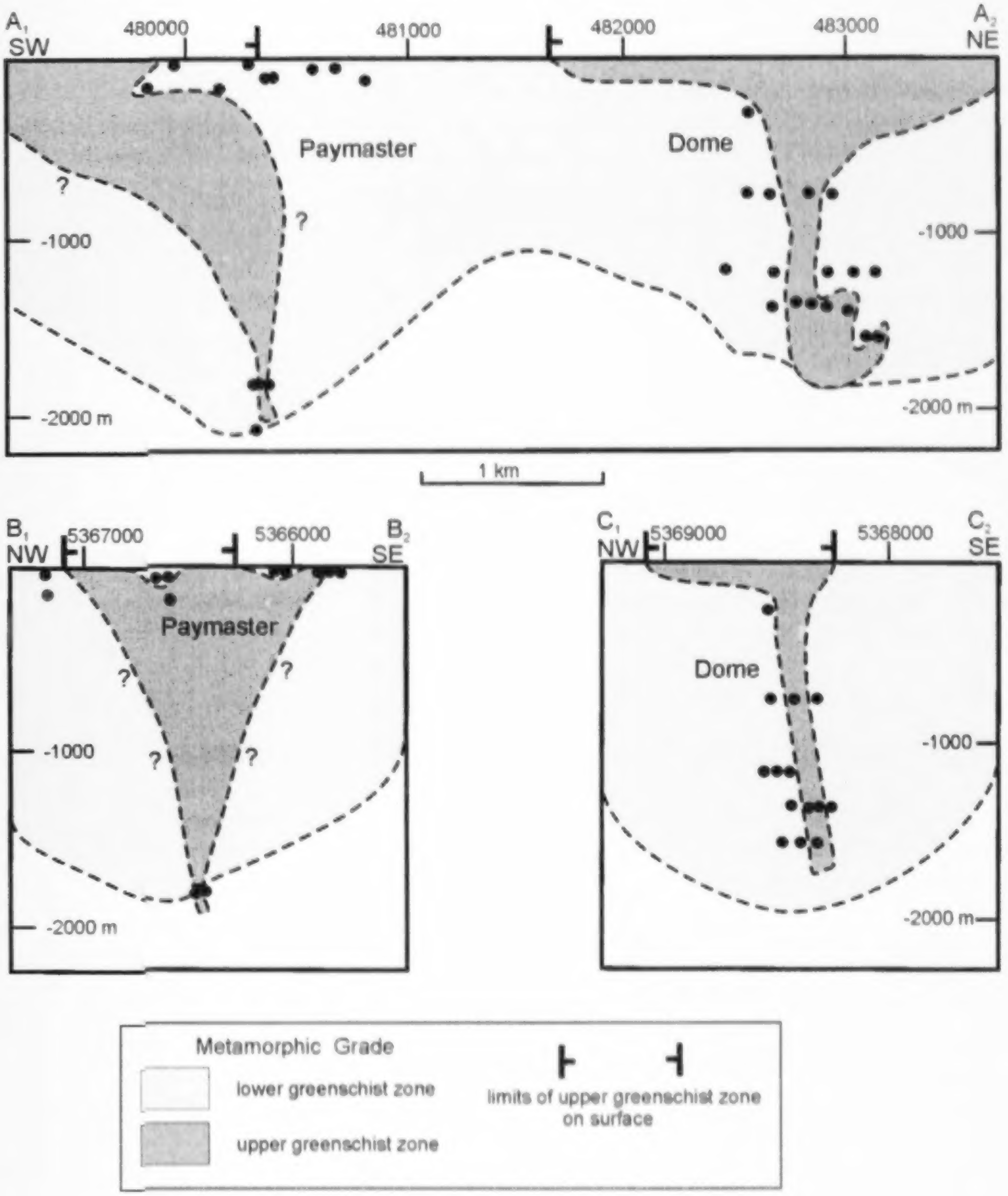
A_1
SW
480000
481000
482000
483000
A_2
NE
Paymaster
Dome
?
?
-1000
-2000 m
-1000
-2000 m
1 km
B_1
NW
5367000
5366000
B_2
SE
Paymaster
?
?
?
?
-1000
-2000 m
C_1
NW
5369000
5368000
C_2
SE
Dome
-1000
-2000 m
Metamorphic Grade
lower greenschist zone
upper greenschist zone
limits of upper greenschist zone on surface

Figure 45.3. Underground data projected onto vertical profiles oriented parallel and perpendicular to the main structural trend through the Dome and Paymaster mines. Note speculative nature of profiles for the Paymaster Mine.

METAMORPHIC ZONE BOUNDARIES AND MINERALIZING(?) FLUIDS

Under greenschist- and amphibolite-facies metamorphic conditions, the changes in mineral assemblage that accompany metamorphic dehydration and decarbonation generate large amounts of fluid (Spear 1993). As concentration of fluid flow is a key element in the formation of ore deposits, it is possible that gold deposits are located on or near metamorphic zone boundaries because metamorphic fluid flow is concentrated near these features.

Many fluid-producing metamorphic reactions are associated with a negative change in the volume of solid phases as generally higher density, less hydrated and/or carbonated minerals grow at the expense of chlorite, white mica and carbonate. If, during metamorphism, fluid pressure is equal to lithostatic pressure in the vicinity of an isograd (Figure 45.4), it is conceivable that the combination of high fluid production and negative volume change of the solids produces a more porous, relatively permeable zone which focuses and enhances fluid flow. At the scale of a greenstone belt, therefore, individual zone boundaries are prospective hosts for syn-metamorphic gold deposits.

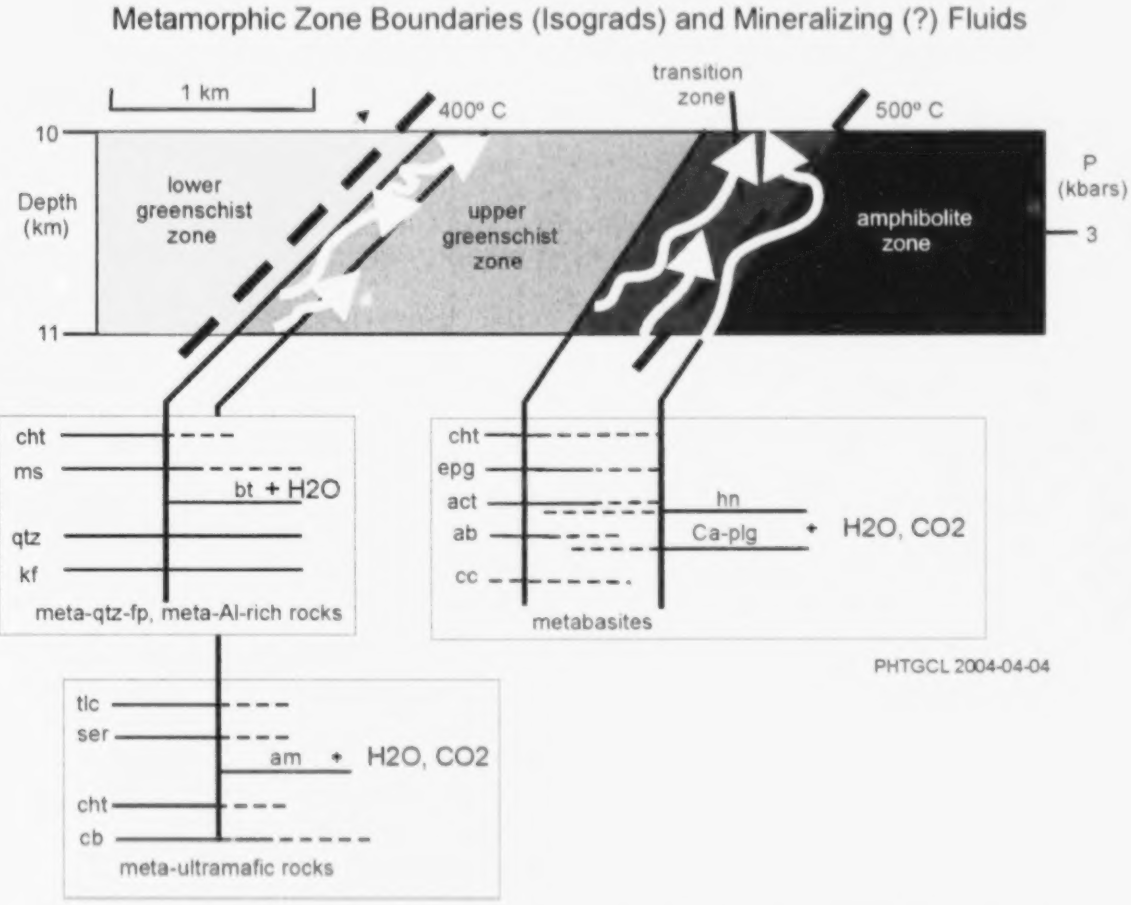
Metamorphic Zone Boundaries (Isograds) and Mineralizing (?) Fluids
1 km
400° C
transition zone
500° C
10
Depth (km)
11
lower greenschist zone
upper greenschist zone
amphibolite zone
P (kbars)
3
cht
ms
bt + H2O
qtz
kf
meta-qtz-fp, meta-Al-rich rocks
cht
epg
act
ab
cc
hn
Ca-plg
+ H2O, CO2
metabasites
PHTGCL 2004-04-04
tlc
ser
am + H2O, CO2
cht
cb
meta-ultramafic rocks

Figure 45.4. Schematic reconstruction of fluid flow regime in vicinity of metamorphic zone boundaries. Abbreviations as in Table 45.1.

METAMORPHIC ZONE BOUNDARIES AND MINERALIZING(?) FLUIDS

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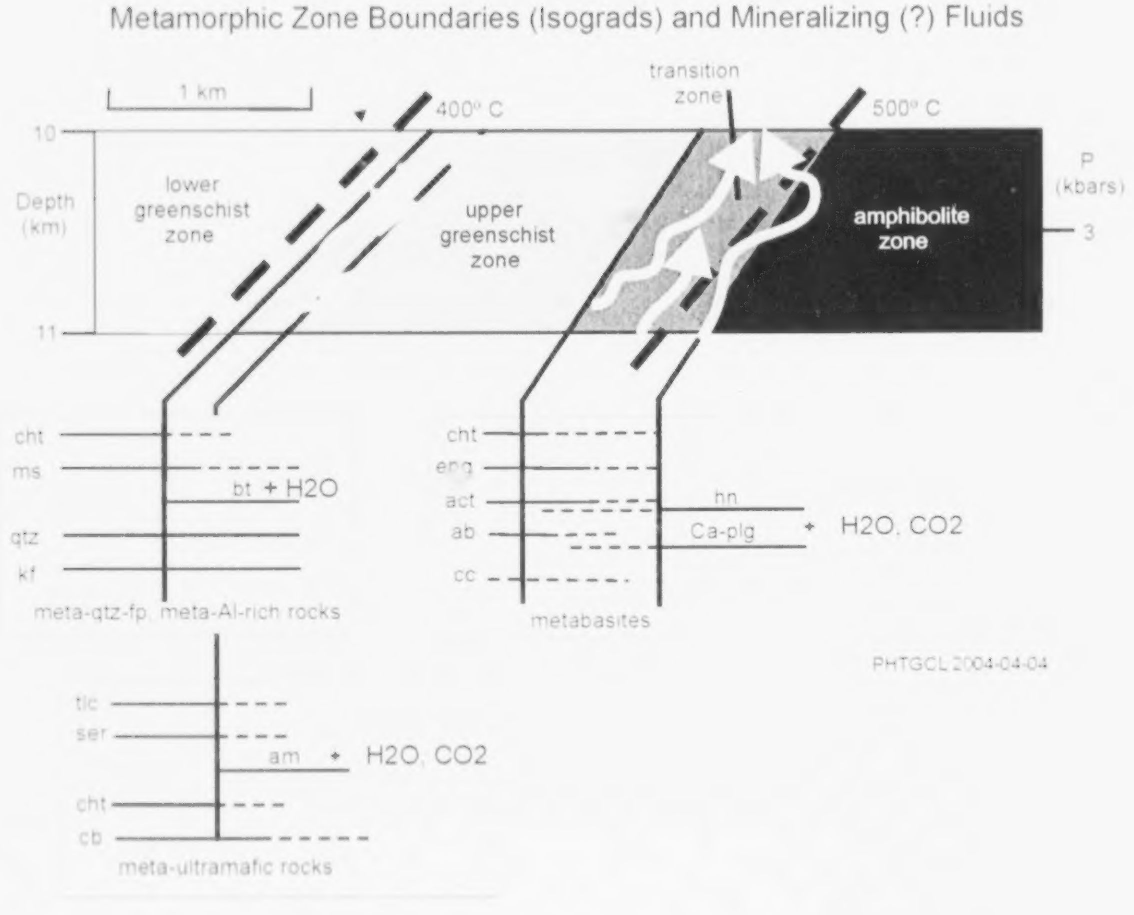
Metamorphic Zone Boundaries (Isograds) and Mineralizing (?) Fluids
1 km
400° C
transition zone
500° C
10
11
Depth (km)
lower greenschist zone
upper greenschist zone
amphibolite zone
P (kbars)
3
cht
ms
bt + H2O
qtz
kf
meta-qtz-fp, meta-Al-rich rocks
cht
epg
act
hn
ab
Ca-plg
+ H2O, CO2
cc
metabasites
tlc
ser
am + H2O, CO2
cht
cb
meta-ultramafic rocks

PHTGCL 2004-04-04

Figure 45.4. Schematic reconstruction of fluid flow regime in vicinity of metamorphic zone boundaries. Abbreviations as in Table 45.1.

Metamorphic anomalies occur as "hot" and "cold" spots (higher metamorphic grade rocks surrounded by lower grade rocks, and lower grade rocks located in a higher grade zone) and in areas where the spacing between metamorphic zone boundaries narrows dramatically. For example, eight of the current and past producing gold mines are associated with higher metamorphic grade anomalies defined by the boundary between the lower and upper greenschist zones (*see* Figure 45.1). In the southeast part of the map area, a gold occurrence in the transition zone is close to a lower greenschist zone cold spot. Presumed to mark steep thermal gradients that may be associated with focussing of the flow of heat and fluid, closely spaced regional isograds and kilometre-scale metamorphic anomalies are also prospective hosts for gold (e.g., Campbell–Gold Corp Mine at Red Lake, Thompson 2003a).

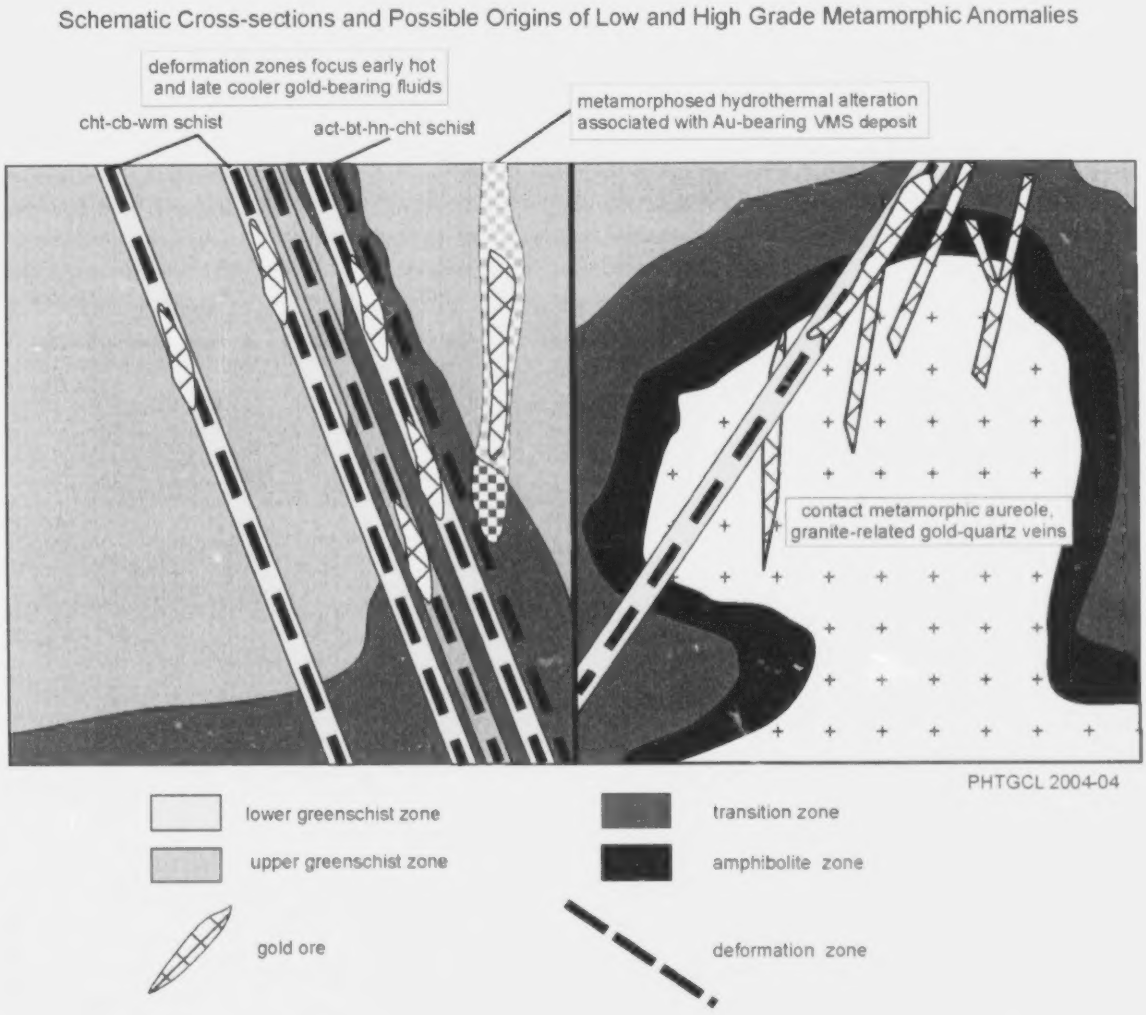
Schematic Cross-sections and Possible Origins of Low and High Grade Metamorphic Anomalies
deformation zones focus early hot and late cooler gold-bearing fluids
cht-cb-wm schist
act-bt-hn-cht schist
metamorphosed hydrothermal alteration associated with Au-bearing VMS deposit
contact metamorphic aureole, granite-related gold-quartz veins
PHTGCL 2004-04
lower greenschist zone
upper greenschist zone
transition zone
amphibolite zone
gold ore
deformation zone

Figure 45.5. Schematic representation of possible origins for high-grade and low-grade metamorphic anomalies.

METAMORPHIC ANOMALIES + TYPES OF GOLD MINERALIZATION

A high metamorphic grade anomaly may be related to a buried syn-orogenic pluton (Figure 45.5). In this case, both granite and porphyry-related gold deposits and metamorphogenic deposits associated with contact metamorphism of the country rock are worth looking for. Alternatively, the relatively high-grade zone may reflect anomalously high fluid flow during regional metamorphism. That is, during ductile deformation, a relatively competent pre-orogenic granitoid develops a fracture system that focusses and enhances subsequent metamorphic fluid flow. These observations may apply to gold mineralization associated with relatively high-grade rocks in the southeast corner of the map area and in between the Faymar and Naybob mines (*see* Figure 45.1) where granitoid rocks are present. Intrusive granitoids are, however, absent from most of the map area (Ayer and Trowell 1998; Ayer, Berger and Trowell 1999).

In areas of uniform metamorphic grade, metamorphosed hydrothermal alteration associated with gold-rich volcanic-associated massive sulphide deposits forms characteristic metamorphic mineral assemblages that distinguish metamorphosed alteration from adjacent unaltered metavolcanic rocks (*see* Figure 45.5). The distinctive mineralogy changes with increasing metamorphic grade but remains a mappable exploration target. Although this kind of metamorphic anomaly may occur elsewhere in the Discover Abitibi project area, no unequivocal examples were found in the thin sections on which the Timmins East metamorphic map is based.

Deformation zones formed at various times during the metamorphic evolution of a greenstone belt have the potential to focus and control fluid flow in ways that are conducive to formation of "shear zone-hosted" gold deposits (*see* Figure 45.5). For example, a linear array of metamorphic "hot spots" could mark the tendency for hot metamorphic fluids to rise more rapidly in particular segments of a deformation zone than heat related to regional metamorphism is conducted through adjacent rocks. The linear array of upper greenschist anomalies in the western half of the map (*see* Figure 45.1) could be explained in this way. Alternatively, the "hot spots" may coincide with litho-structure conduits that have conveyed hydrothermal fluids relatively rich in CO_2 toward the surface. Dehydration reactions such as those that produce biotite (*see* Figure 45.4) occur at lower temperatures in the presence of such fluids. In this case, temperatures prevailing when the upper greenschist zone anomalies formed may have been equal to those in surrounding lower greenschist zone rocks. That is, the metamorphic anomaly may reflect anomalous amounts of CO_2-rich fluid flow rather than higher temperatures. In contrast, isolated "cold spots" or linear arrays of relatively low metamorphic grade anomalies could be imposed on higher grade rocks as retrograde metamorphism after the mineral assemblages have been fixed in the rocks and uplift and erosion are bringing the cooling rocks back to the Earth's surface. Anomalous lower greenschist zone rocks associated with the amphibolite zones in the southeast (*see* Figure 45.1) and with the two transition zone anomalies in the northwest may be examples of this process.

METAMORPHISM AND ALTERATION

The relationship between metamorphism and alteration is complex. For the purposes of this project, alteration is viewed as a type of metamorphism (hydrothermal metamorphism) that has a relatively restricted distribution, involves movement of components other than water and carbon dioxide in and out of the rock, and is associated with anomalously high volumes of fluid. Typically, it is controlled by structure and/or lithology and may occur before, during or after regional and contact metamorphism. In the course of regional petrography, samples with atypical mineralogy such as felsic metavolcanic rocks with high white mica content, tourmaline-rich metasedimentary rocks, very aluminous compositions and carbonate-rich rocks are noted. For example, in the vicinity of the Dome Mine (*see* Figure 45.2), carbonate-rich rocks (rock association 7) stand out. Many of these rocks are intensely foliated and may be the classic chlorite-carbonate-white mica schist and phyllite that occur in the mineralized high strain zones that are associated with many Archean gold deposits. Textural and mineralogical evidence is consistent with formation of these rocks during regional metamorphism by reaction between greenschist zone metabasites (actinolite-chlorite-epidote-albite greenstones and/or metagabbro), meta-ultramafic rocks and CO_2-rich hydrothermal fluids of metamorphic and/or igneous origin (e.g., Clark et al. 1989). In this case, high CO_2 fluid generates "lower grade" carbonate-chlorite assemblages at the expense of "higher grade" actinolite and epidote at peak regional metamorphic temperatures. Once again, the metamorphic anomaly reflects changing fluid compositions rather than changing temperatures. This means that, in metabasites, chlorite-carbonate rocks are not necessarily late retrograde features, but could be products of the thermal and fluid flow regimes that prevail during peak conditions of regional metamorphism. This is an appealing idea because the opportunity for enhanced fluid flow is higher during metamorphism than after the rocks have begun to cool.

METAMORPHIC TARGETS FOR GOLD EXPLORATION

As is the case west of Timmins (Thompson 2002) and in the Red Lake greenstone belt (Thompson 2003a), the boundary between the lower and upper greenschist zones to the east of Timmins (*see* Figure 45.1) also has the potential to host gold mineralization. It is important to note, however, that data density varies greatly across the map and that the position of the boundary is subject to revision. In any case, a significant proportion of past and current gold producers occur on or near the boundary where it outlines higher grade zones tens of kilometres wide and where it defines metamorphic "hot spots". Although only a few of the known gold occurrences are included on the map, several of them occur on or near the lower–upper greenschist zone boundary (e.g., Tully Township). The transition zone in the east half of the metamorphic map area (*see* Figure 45.1) contains gold occurrences, as is the case at Red Lake.

If the proposed relationship between gold mineralization and metamorphic zonation is supported by further work, the areas where key metamorphic zone boundaries intersect rock units and structures that are already known to host gold mineralization will be of particular interest for gold exploration. For example, the spectacular concentration of gold mines east of Timmins (Tisdale and Whitney townships) corresponds to the intersection of a northeast-trending array of metamorphic anomalies, a large mass of mafic and ultramafic meta-igneous rocks, and a major bend in the Porcupine–Destor Fault (*see* Figure 45.1). In this regard, it may be significant that there is a suggestion of a northeast-trend in the irregular shape of the northwestern greenschist zone where it overlaps the contact between metasedimentary and mafic to ultramafic metavolcanic rocks in the north (southwest corner of Tully Township, northeast corner of Wark Township) and metamorphosed ultramafic rocks to the south (compare Figure 45.1 with the Ayer and Trowell (1998) geological compilation map for the area). Two of the four gold occurrences present are shown on the metamorphic map. Furthermore, the northeast metamorphic anomaly that contains a gold occurrence in the transition zone (Dundonald Township), which may be an extension of the mineralized metamorphic trend to the southwest. Once again, the relatively high metamorphic grade rocks overlap the contact between metasedimentary and mafic metavolcanic rocks.

Chlorite-carbonate-rich rocks, widely interpreted to be products of the hydrothermal metamorphism of metabasites and meta-ultramafic igneous rocks by CO_2-rich fluids, are prominent in the mineralized zones of the Dome Mine (*see* Figure 45.2), a gold deposit that is associated with a relatively high-grade metamorphic anomaly. Similar rocks occur elsewhere in the map area (Thompson 2004, Figure 2) where gold mineralization and metamorphic hot spots are absent. Both features are, on their own, consistent with anomalously high fluid flow.

In the search for very large gold deposits, perhaps it is the combination of extensive carbonate-rich altered rocks and a metamorphic anomaly that would make the best target. Five kilometres east of the Dome Mine (approximately 3 km south of the Hunter Mine, *see* Figure 45.1), there is an abundance of carbonate-rich rocks (Thompson 2004) and a small metamorphic "hot spot", but no known gold occurrences according to Ayer and Trowell (1998). Further exploration of this locality will be an important test of the idea that the combination of upper greenschist zone metamorphic anomalies and extensive syn-metamorphic carbonate alteration is a means of targetting the zones of anomalous fluid flow that are associated with large gold deposits. As noted above, the occurrence of chlorite-carbonate rocks near gold occurrences associated with the lower–upper greenschist zone boundary of the northwest higher grade metamorphic zone provides another test case.

FUTURE WORK

The final metamorphic map will include 1) data from approximately 2000 thin sections; 2) data from previous work completed west of Timmins (Thompson 2002); 3) all gold occurrences and current and/or past producers; 4) pre-orogenic, early syn-orogenic, and late syn-orogenic granitoids. The accompanying database will include observations relating to alteration and intensity of deformation. Depth–time analysis of metamorphism, deformation, magmatism and exhumation will provide a new perspective on the geological setting and evolution of gold mineralization. Publication of the final map and Open File Report is planned for 2005.

For a regional-scale project like this, it is necessary to balance the conflicting demands of covering the designated area and of obtaining a data density adequate to define reasonably well-constrained metamorphic exploration targets. Definition of many of the metamorphic anomalies that have gold potential in the Timmins East metamorphic map area can and should be improved with additional sampling in key target areas.

In view of the results summarized here, priority areas for more detailed work include 1) northwest upper greenschist zone, 2) northeast extension of the gold-rich trend of metamorphic anomalies located east and northeast of Timmins, 3) data gaps northeast and southwest of the Aquarius Mine, 4) lower–upper greenschist boundary and metamorphic cold spots at the north end of the southeast amphibolite zone (*see also* Thompson 2003b).

ACKNOWLEDGMENTS

The project benefits directly from earlier work supported by the Ontario Geological Survey and Placer Dome Group west of Timmins (John Ayer, Greg Hall, Richard Keele) and in the Red Lake area (Yuri Dubrotin, Greg Hall, Jack Parker). Financial and logistical support for Discover Abitibi from Porcupine Joint Venture, Falconbridge Limited, Laurentian University, Timmins Economic Development Corporation, Northern Ontario Heritage Fund Corporation, and FedNor Canada are much appreciated. To date, Brian Atkinson, John Ayer, Erik Barr, Roger Bateman, Ben Berger, Vladimir Ispolatov, Lindsay Hall, Michel Houlé, Gerhard Meyer, Tom Muir, Frank Santaguida, and Christine Vaillancourt have contributed thin sections, an essential component of the project. Critical reviews by John Ayer and Phil Thurston improved this report.

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46. Discover Abitibi. Preliminary Results of the Geology and Geochemistry of the Volcanic Rocks Hosting the Hoyle Pond Mine, Timmins, Ontario

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INTRODUCTION

The Hoyle Pond gold mine is located in southeastern Hoyle Township, approximately 15 km northeast of Timmins, Ontario. The mine is currently owned by the Porcupine Joint Venture and has been in continuous operation since 1985. The mine is situated in a suite of metavolcanic rocks that forms part of the Tisdale assemblage (2703 to 2710 Ma: Ayer et al. 2002) dominated by tholeiitic mafic metavolcanic to ultramafic metavolcanic rocks, intruded by younger quartz-albite porphyries. The Tisdale assemblage rocks are bounded by metamorphosed clastic sedimentary rocks of the Porcupine assemblage (circa 2685 Ma) to the north and south. At present, two main ore zones are recognized, based on host rock composition, structure and style of alteration (Pressacco 1999). The first zone consists of quartz veins associated with a graphitic style of alteration (so called "grey zone") hosted mainly in Mg-tholeiite flows. The second zone consists of a number of veins associated with the 1060 fault zone in mafic to ultramafic volcanic rocks intruded by a younger felsic intrusion.

During the summer of 2003, detailed mapping and sampling of the 440 m level was completed enabling the separation of the mine geology into 3 zones or packages. The north volcanic package is dominated by a sequence of massive, pillowed, variolitic pillowed flows and flow breccias. The central volcanic package consists of two ultramafic volcanic rocks units interlayered with mafic volcanic rocks. The south volcanic package is dominated by massive flows, pillowed flows and volcaniclastic rocks. The geochemical characteristics of the packages are given below. Figure 46.1 shows the geology of the 440 m level at the Hoyle Pond Mine. Initially, it was thought that the central volcanic package was the core of an antiform, however, the results of this project (discussed below) indicate it could also be a homoclinal sequence of stacked volcanic flows. The aim of this project, which constitutes an on-going PhD at the University of Ottawa, is to determine the nature of the Tisdale assemblage lithologies in the mine area and correlate them with larger deposits previously mined in the Timmins Camp (Hollinger and McIntyre mines). In addition, the host-rock controls on mineralization and the geochemistry of alteration is being investigated in detail.

NORTH VOLCANIC PACKAGE

Figure 46.2d is a Jensen diagram showing that the north volcanic package is dominated by rocks having Mg-tholeiite geochemical signatures with minor amount of basaltic komatiites. The rare earth element (REE) patterns (Figure 46.2a) are complex and variable. However, in general, they have an open concave pattern with negative sloped light rare earth element (LREE) (La to Sm) and negative Eu anomalies. The heavy rare earth elements (HREE) are more enriched than the LREE and have a positive

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.46-1 to 46-4.

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slope. Chondrite-normalized ratios for the LREE and HREE vary from 2 to 13× chondrite and from 6 to 20× chondrite, respectively. Although most samples display negative Eu anomalies, some have positive Eu anomalies.

CENTRAL VOLCANIC PACKAGE

Two distinct ultramafic volcanic units were identified in this package during underground mapping on the 440 m level (*see* Figure 46.1). In terms of the Jensen diagram, the geochemistry shows a variation from basalt to basaltic-komatiite to ultramafic komatiites (Figure 46.2b). All specimens have chondrite-normalized REE spectra less than 10× time chondrite. The chondrite-normalized abundance of LREE increases with atomic number though the distribution on the log-plot is curved rather than linear. The HREE patterns have less curvature and a decrease in concentration from Dy to Lu. Some samples have slight positive Eu anomalies, whereas the majority have small negative Eu anomalies.

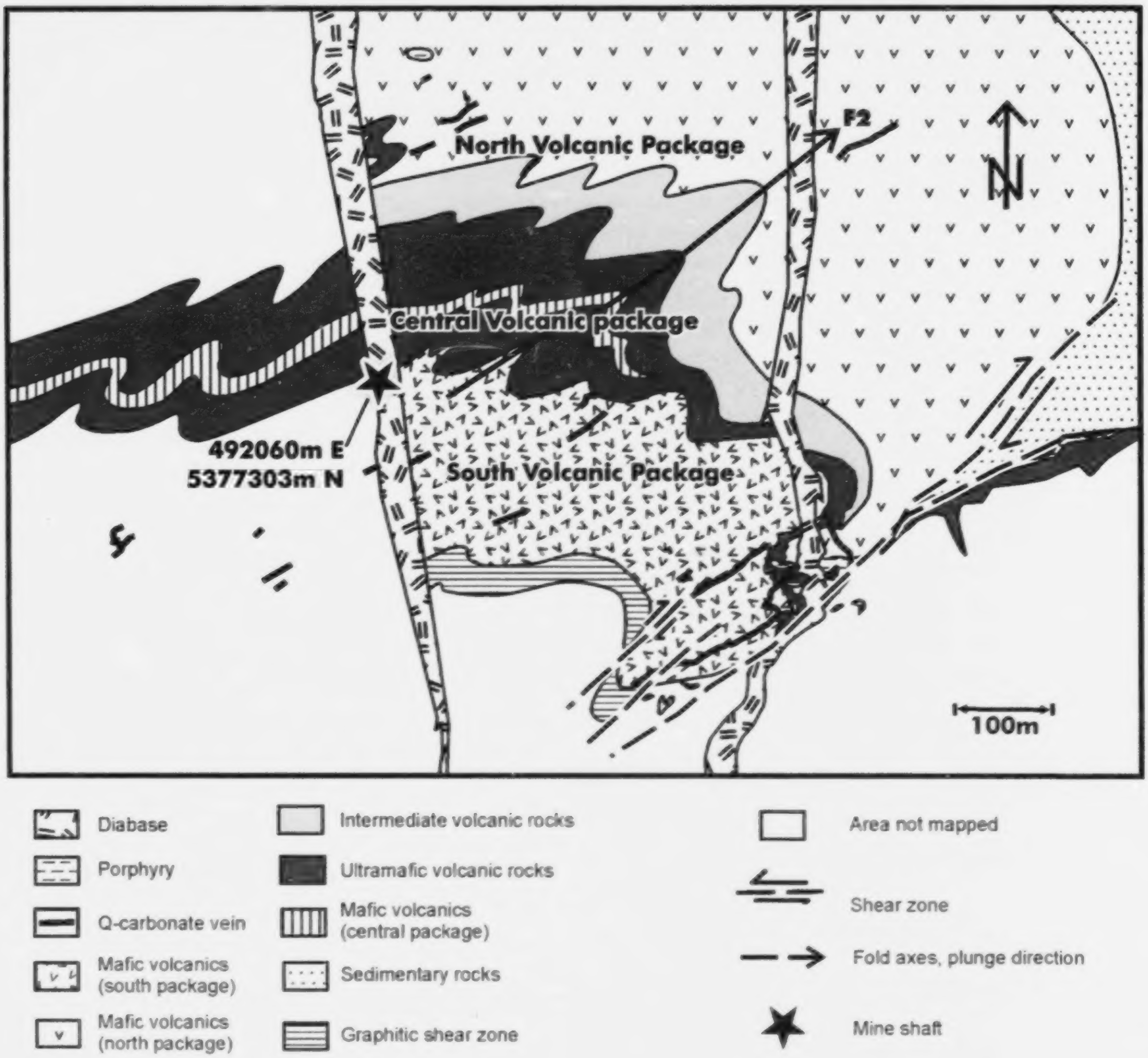
North Volcanic Package
F2
N
Central Volcanic package
492060m E
5377303m N
South Volcanic Package
100m
Diabase
Porphyry
Q-carbonate vein
Mafic volcanics (south package)
Mafic volcanics (north package)
Intermediate volcanic rocks
Ultramafic volcanic rocks
Mafic volcanics (central package)
Sedimentary rocks
Graphitic shear zone
Area not mapped
Shear zone
Fold axes, plunge direction
Mine shaft

Figure 46.1. Preliminary geology of the Hoyle Pond Mine, 440 m level.

SOUTH VOLCANIC PACKAGE

The south volcanic package is found south of the shaft in the mine at the 440 m level. It is dominated by massive and pillowed flows plus flow breccias that are mafic in composition. According to the Jensen classification (*see* Figure 46.2d), the various flows are Mg-tholeiite in composition, with the exception of an iron-rich tholeiitic basalt which hosts the mineralization in the 440 to 950 m zones. This particular unit is traceable for more then 300 m; it is conformable to the stratigraphy and therefore these geochemical characteristics are not interpreted to be due to alteration. The chondrite-normalized REE patterns indicate two different groups (Figure 46.2c). The general pattern is linear with a positive slope and a slight negative Eu anomaly, but also rarely with positive Eu anomalies. In both groups, chondrite-normalized LREE vary from 5 to 20× chondrite, whereas the HREE form two distinct patterns, with one ranging from 10 to 14× chondrite and the other from 17 to 36× chondrite. The nature of this HREE distinction between the two groups will be investigated further. Two felsic units were found within the south volcanic package, a quartz-albite porphyry (QFP) and a quartz porphyritic sericite schist. The QFP is intrusive having discordant contacts and containing zircons that yield a preliminary U/Pb age of 2683 Ma (M.A. Hamilton, Jack Satterly Geochronology Laboratory, University of Toronto, personal communication, 2004). This age is clearly younger than the enclosing Tisdale assemblage volcanic rocks and slightly younger than most other QFP in the Timmins gold camp (Macdonald, Piercey and Hamilton, this volume). In contrast to the QFP, the quartz porphyritic sericite schist is strongly foliated and sericitized and appears to be conformable with the adjacent mafic and ultramafic volcanic units over 200 m (horizontal and vertical). The millimetre-scale quartz phenocrysts are embayed, a dissolution texture common in quartz-phenocryst-bearing volcanic rocks. Additional geochronology data from this unit are pending, results of which should determine if the sericite schist is part of the Tisdale assemblage stratigraphy, or a QFP intrusion.

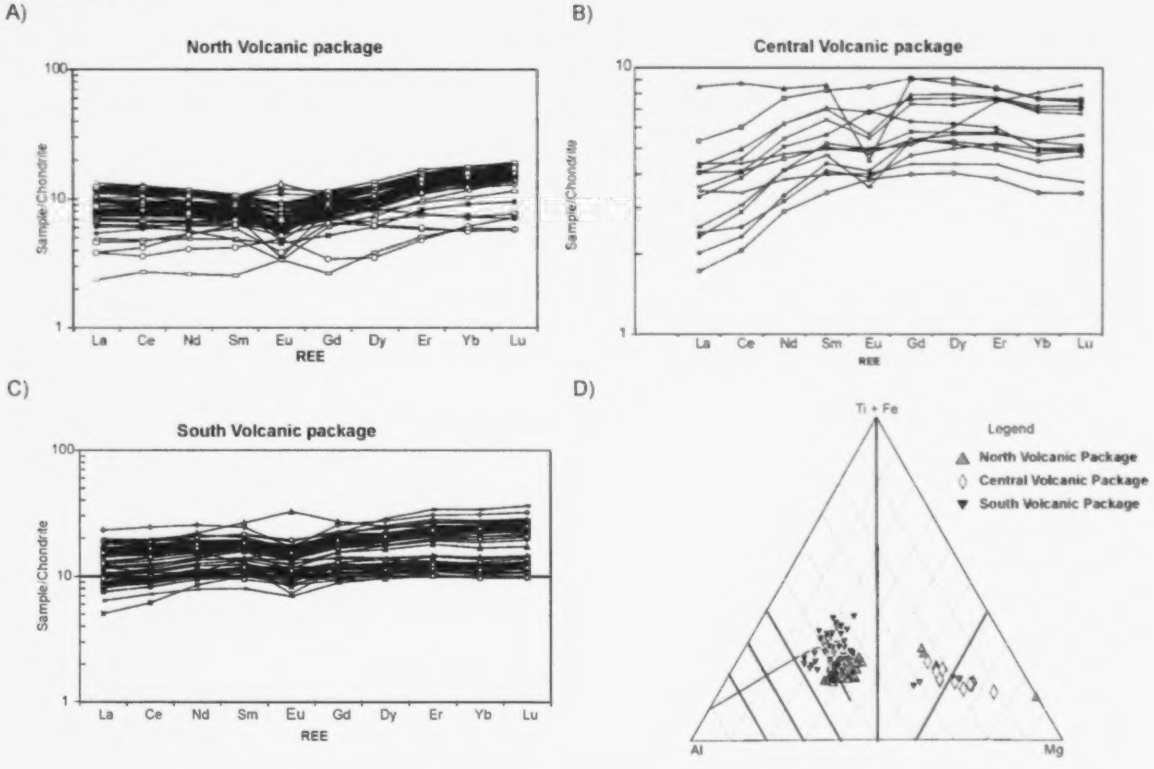

Figure 46.2. Rare earth element and Jensen plots of samples from the Hoyle Pond Mine volcanic packages.

STYLES OF AURIFEROUS VEINING

In the north volcanic package, strain is confined to narrow zones of 5 to 10 m width which host quartz-carbonate gold-bearing veins. The graphitic alteration zones are restricted to high porosity rocks either formed by shearing and/or by the primary porous nature of the volcaniclastic units. In the south volcanic package, the strain is pervasive, though at different intensities in various units. The more intense shear zones are spread out in an anastamosing structure. The vein orientations are mostly 070° with some north to south sigmoidal veins defining a C-S type pattern and a sinistral sense of shear in the 1060 fault. This could have resulted from late movement during the deformation. In the south volcanic package, an extensive 10 to 20 m wide graphitic zone that was previously thought to be interflow sediment has been shown to crosscut stratigraphy. It is now interpreted to be a remnant of an early shear structure. Numerous veins within the south volcanic package terminate against this graphitic zone leading to the interpretation that its physical properties terminated vein propagation. In the central volcanic package, a mafic volcanic unit was found between ultramafic volcanic units. It is likely that the competency contrast between these different lithologies may have localized mineralization (i.e., the UM vein).

SUMMARY

The rocks in the mine are dominated by Mg-tholeiites, Fe-tholeiites, basaltic komatiites and ultramafic komatiites. The north volcanic package is dominated by Mg-tholeiites whereas the south volcanic package is dominated by Mg-tholeiite and Fe-tholeiites. Thus, the central volcanic package is no longer interpreted to be within the core of an early antiform as the lack of symmetry in the composition of the rocks on either side of the central volcanic package provides evidence that the rocks hosting the mine are a homoclinal stratigraphic package which were subsequently tightly folded around northeast-trending folds near the 1060 fault zone.

FUTURE WORK

Detailed geological mapping of the 3 level, 440 m level, 720 m level and 880 m level will be completed. A high-resolution analysis of the geochemical data will be achieved using advanced statistical methods to characterize the alteration patterns and elemental mobility. This will be combined with the data on mineralogy and mineral chemistry of the rock in order to understand the nature of the mineralizing fluids.

ACKNOWLEDGMENTS

We acknowledge John Ayer, Jack Parker and the OGS Geoscience Laboratories for providing technical support and some of the geochemical analyses. We thank Alastair Still, Michael Nerup, Erik Barr, Ken Tylee, Ivan Langlois, Richard Allard, Mike Simunovic, Andre Verville and Keith Green from Porcupine Joint Venture for their technical support, in particular guidance for the underground work and providing some of the geochemical analyses and David Rhys for constructive criticism. E.D. especially thanks his assistant, Benoit Saumur, who helped during mapping and sampling and in sample preparation.

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Lake Nipigon Region Geoscience Initiative

47. Breaking New Ground in Collaborative Geoscience: An Update on the Lake Nipigon Region Geoscience Initiative

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INTRODUCTION

The Ontario Prospectors Association (OPA) in collaboration with the Ontario Geological Survey (OGS), Lakehead University, mineral industry and government partners are undertaking, with financial support from the Northern Ontario Heritage Fund Corporation, a two-year program of geoscience studies in the Lake Nipigon region.

This collaboration commenced with a request through the Ontario Geological Survey Advisory Board (OGSAB) to look into the delivery of geoscientific information by way of a collaborative effort between the mineral sector, government and universities in the Lake Nipigon region. The Ontario Prospectors Association was identified as the group to manage this program. The Lake Nipigon Region Geoscience Initiative (LNRGI) is a science-based geological data acquisition and compilation study that will conduct research and collect new geoscientific observations that will explain the geological history of the area. It will also identify high mineral potential targets in the region that will attract exploration to the region, outside of the parks and conservation reserve areas.

FOUNDATIONS FOR COLLABORATION

In order to evaluate the geoscience gaps, a request for membership to populate the Lake Nipigon Science Committee was sent out to the companies who were part of the original client consultation process conducted by the OGS. Remarkable enthusiasm was shown by industry and government for the project. In total, 16 people plus 5 alternates came together to form the Science Committee. The Science Committee is represented as follows: 5 from industry, 2 from Lakehead University, 4 from OGS, 3 from industry consultants (geology, geophysics and GIS), and 2 from First Nation communities.

Through a request for proposal, CAMIRO was contracted to provide technical analysis of the deliberations of the Science Committee and to insure the science gaps identified were accurately documented. CAMIRO also provides technical support to the LNRGI Program Director.

IDENTIFYING AREAS OF COLLABORATION

At the point of preparing the request for funding for the project, several areas of collaboration were identified even before the formation of the Science Committee. The Ontario Geological Survey and Lakehead University were identified as key partners. The number one priority identified in the client

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.47-1 to 47-8.

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consultation was the need for bedrock and stratigraphic mapping. Gaining an understanding of the geological history of the western Lake Nipigon Embayment became the key directive. This would naturally lead to an assessment of the possible mineral deposit models for the region and their economic potential.

Lakehead University professors with extensive experience in the Lake Nipigon region were approached to sit on the Science Committee and provide project proposals to address the stratigraphic and mafic intrusive problems. Three of four proposals were recognized as key studies that addressed the key directive.

The OGS would provide bedrock mapping for 2 of 4 map areas as in-kind support to the collaborative mapping project. The Ontario Prospectors Association contracted 2 additional map areas to GEOEnterprises Ontario and the OGS through a request for proposal bid process. The selection of this group insured all bedrock mapping would be done to the high standard set by the OGS.

Access to the land base required building collaboration in 2 areas. Access to the First Nation traditional land and specifically the Gull Bay First Nation Reserve was necessary, as was access to the Parks and Conservation Reserves managed by the Ministry of Natural Resources.

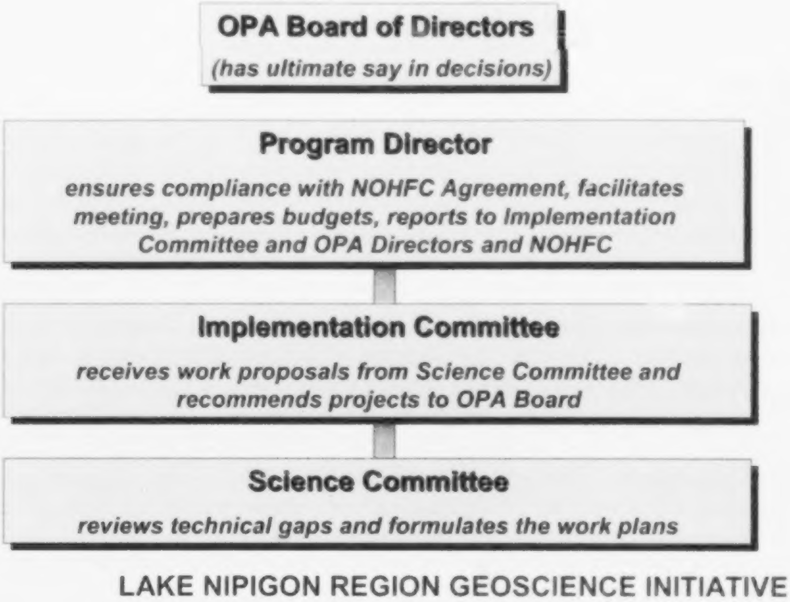
An important collaboration was established with the Ministry of Natural Resources to enable the continuity of collection of geoscientific data over the areas of Conservation Reserves and Provincial Parks. Permission was gained through a Research Application.

Gull Bay First Nation was identified as the community with most interest in the land base of the western Nipigon Embayment area. Information sessions were held in the community to explain the purpose, objectives and predicted results of the Lake Nipigon Region Geoscience Initiative. The Chief and Band Council were supportive of the project, and provided valuable insight to community concerns.

To address the pressing question of how the Nipigon Embayment formed, a collaborative project with the Geological Survey of Canada was established to carry out deep seeing magnetotelluric geophysical surveys and paleomagnetic studies on mafic intrusive rocks. The magnetotelluric survey will provide information regarding the crust thickness as well as major structural and lithologic features found along the lithoprobe traverses. The palemagnetic study of mafic dikes in the Nipigon Region will provide age correlation with other intrusive activities in Northwestern Ontario.

PUTTING PLANS IN ACTION

The overall science gaps identified were followed up with written proposals that were discussed by the Science Committee. In most cases, the authors of the proposals were asked to amend the proposal and provide estimates of the cost to carry out the project. Once the project was selected by the Science Committee, it was presented to the next level of program management, that being the Implementation Committee. This group of managers were representatives of the Board of Directors of the Ontario Prospectors Association, Lakehead University, Ontario Geological Survey, Ontario Geological Survey Advisory Board, mineral industry and First Nations. Once a project was approved by the Implementation Committee, then the project was presented to the Board of Directors of the OPA for approval. Figure 47.1 shows the management structure for the Initiative.



OPA Board of Directors
(has ultimate say in decisions)

Program Director
ensures compliance with NOHFC Agreement, facilitates meeting, prepares budgets, reports to Implementation Committee and OPA Directors and NOHFC

Implementation Committee
receives work proposals from Science Committee and recommends projects to OPA Board

Science Committee
reviews technical gaps and formulates the work plans

LAKE NIPIGON REGION GEOSCIENCE INITIATIVE

Figure 47.1. Management structure for the Lake Nipigon Region Geoscience Initiative.

GEOSCIENCE IMPORTANCE OF THE REGION

The Lake Nipigon region is of interest to the Ontario, Canadian, and international geological community because the rocks appear to preserve evidence for the rifting of the Earth's surface approximately 1 billion years ago. The Nipigon area is presently interpreted to be the failed third arm of a major Proterozoic rift (Keweenawan Supergroup) that transects mid-continent North America beneath Lake Superior. Documented evidence of crustal rifting processes preserved the Lake Nipigon region and will enhance the understanding of the geological history of this immediate area and the geological history of rocks preserved south of Thunder Bay, into the United States. Data collected for this project will be used by the Ontario Geological Survey (OGS) as part of their five-year core business commitment to the area and as part of a joint OGS–United States Geological Survey (USGS) project to compile and understand the geological history of the entire Midcontinent Rift system.

Elsewhere in the world, similar Earth processes have concentrated metals in the crust, including nickel-copper, platinum group metals, copper-gold, gold, and rare metals, to levels where they form economically viable ore deposits. Important insights gained by studying this region will be applied to more effectively explore for mineral resources in this region and elsewhere in Ontario.

RATIONALE FOR THE PROGRAM

Several specific geoscience questions will be addressed during this study. Part of our existing knowledge gap is due to the fact that much of the study area has not been mapped or sampled in detail. For example, undocumented areas of Archean rocks have been reported from the study area, but until the character and distribution of these rocks are known, they have unknown mineral potential. Also, the Sibley Group of sedimentary rocks and the English Bay felsic intrusion contain the oldest elements of the

Keweenawan rift system. These studies will aid our understanding of the relationship of these elements and their implications for resource potential. In addition, Operation Treasure Hunt lake sediment geochemistry surveys identified metal anomalies in the area that may be indicative of unknown mineral occurrences. Both the surficial geochemical and bedrock mapping studies will help to determine the cause of these anomalies.

Although the region has undergone recent exploration for Ni-Cu-PGE mineralization associated with mafic intrusions (1100 Ma), it is not known whether mineralization type varies between intrusion forms (e.g., cone sheets versus sills or lopoliths). The distribution of felsic intrusions and related metavolcanic rocks (circa 1530 Ma) in the English Bay area is not well known, nor is the potential for iron-oxide-gold-copper mineralization in association with these felsic intrusions. The Black Sturgeon fault has been suggested as an important controlling factor with respect to distribution of mafic intrusions, and possibly mineralization. Consequently, determining its precise location, as well as comparing stratigraphy across the fault, will be important in determining the metallogenic significance of this structure. Geochemical studies of the mafic intrusions will help in establishing the internal stratigraphy of these units, as well as aiding in determining the processes responsible for mineralization.

The acquisition of high-resolution geophysical data for the Lake Nipigon region as part of this project will not only play a role in defining potential exploration targets, but, when integrated with the bedrock mapping results, will help to better define geological contacts and regional geological structures.

FUNDING

The Lake Nipigon Region Geoscience Initiative received $3.5 million funding from the Northern Ontario Heritage Fund Corporation, which has been matched by in-kind support from local partners.

GOAL OF THE LAKE NIPIGON REGION GEOSCIENCE INITIATIVE

The LNRGI projects will enhance the scientific understanding of the area and facilitate mineral exploration in the region by

- collecting geoscience observations that describe the physical characteristics of the local geology
- providing new detailed maps of the western Nipigon Embayment that integrate geophysical features and are constrained by strategic geochronological data
- providing interpretations of the geoscience data to explain the local geological history
- contributing to a geological synthesis of the region
- advancing the scientific understanding of the region which will provide concepts and methodologies that the mineral exploration community can apply in the Lake Nipigon Region and elsewhere in Ontario and provide a framework for informed future land use decisions
- helping attract interest from international and domestic investors to encourage new mineral exploration investment in high-mineral potential areas in the region and adjacent areas

Local communities have been invited to support and participate in the present geoscience activities. If a new mine is discovered in the region, all communities will benefit from the resulting jobs and other economic benefits.

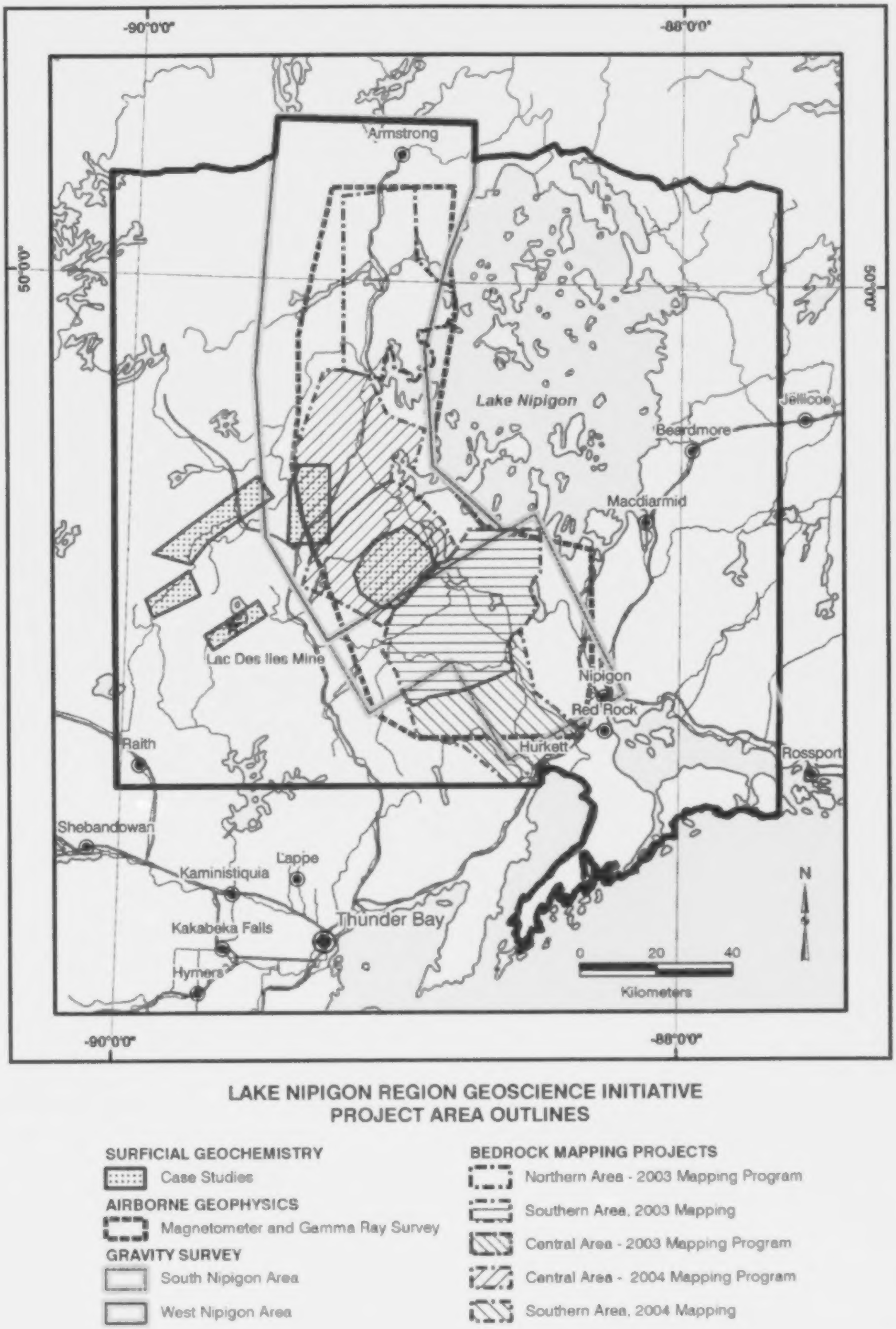
As well, the information gathered from the LNRGI will add to knowledge of the geology of the various protected areas in the Lake Nipigon region. This information will increase knowledge of the natural processes that occurred within the protected areas and will provide a significant resource for future interpretative programs.

Geoscience data will be gathered in a variety of ways using low-flying aircraft, helicopter, all-terrain vehicle (ATV), snow machine or boat. Geoscientists on the ground will be taking measurements with a variety of different instruments, or mapping out and measuring various rock occurrences.

GEOSCIENCE PROJECTS

As of September 22, 2004, the following projects are completed, underway or planned for the Lake Nipigon region. Figure 47.2 shows the area of the LNRGI as well as the boundaries of the geoscience projects described below.

1. Bedrock Mapping: 1:50 000 scale bedrock mapping was completed in 2003. In 2004, additional bedrock mapping will occur in 2 blocks within the western Nipigon area (Hart and Whaley, this volume; MacDonald, Tremblay and Easton, this volume). The projects have been designed to gather geological data over key areas in the western part of the Nipigon Embayment in order to address several geoscience problems. The bedrock mapping is being completed in parks and protected areas within the region under permit from the Ministry of Natural Resources (MNR) and Parks Ontario. Light "foot print" bedrock mapping will be carried out without significant disturbance to the natural environment. Navigation is being done using global positioning systems (GPS). Bedrock outcrops will be located, sampled and described, and key stratigraphic units will be sampled for geochronology. Rock samples are also being collected for determination of rock properties, including density and magnetic susceptibility, for integration with the geophysical surveys. All data collected will be made public, and specific data and maps of the park areas could be reproduced for park use. The results of the bedrock mapping will be incorporated with the other geoscience data to generate an integrated interpretation of the geological history. These data along with geophysical data will contribute to the regional 3-D data analysis to be carried out by the OGS in collaboration with MIRARCO.
2. A petrology project was initiated in 2004 to complement the OGS bedrock mapping, and geological interpretation by analyzing several hundred thin and polished sections from rock samples collected during the mapping. It is expected that a separate petrographic report will be published under the Lake Nipigon Region Geoscience Initiative.
3. Aeromagnetic and gamma spectrometry: This survey was completed on August 28, 2003, and was conducted over a large area west of Lake Nipigon. The fly-over of the Gull Bay First Nation reserve was negotiated with the band council. The MNR permit also acknowledged the fly-over of the parks and protected areas in the region. The results of this project were released on April 9, 2004. Reports and maps have been provided to both the Gull Bay First Nation and Parks Ontario.
4. Gravity Survey: Gravity measurements are being collected throughout the region west of Lake Nipigon. Data from this type of survey help infer the density of rock buried in the crust. This is a ground survey and the access to suitable measurement sites is provided by existing access roads. This survey is regional in nature and the increased density of topographically controlled stations is a key component in creating a geological model to better understand the rock formation history. Of interest will be a gravity profile across the interpreted basin forming growth faults, including the Black Sturgeon fault and several poorly defined structures. The complex relationship of these north-south structures with east-west Archean structures and local development of ovoid PGE-bearing ultramafic intrusions is of high interest. The survey was completed March 2004 and released to the public of September 1, 2004.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Armstrong
Lake Nipigon
Jellicoe
Beardmore
Macdiarmid
Nipigon
Red Rock
Hurkett
Rossport
Lac Des Iles Mine
Raith
Shebandowan
Kaministiquia
Lappe
Thunder Bay
Kakabeka Falls
Hymers
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Kilometers
LAKE NIPIGON REGION GEOSCIENCE INITIATIVE
PROJECT AREA OUTLINES
SURFICIAL GEOCHEMISTRY
Case Studies
AIRBORNE GEOPHYSICS
Magnetometer and Gamma Ray Survey
GRAVITY SURVEY
South Nipigon Area
West Nipigon Area
BEDROCK MAPPING PROJECTS
Northern Area - 2003 Mapping Program
Southern Area, 2003 Mapping
Central Area - 2003 Mapping Program
Central Area - 2004 Mapping Program
Southern Area, 2004 Mapping

Figure 47.2. Area of interest encompassed by the Lake Nipigon Region Geoscience Initiative, as well as the location of the geoscience projects See text for further details.

5. Geochronology: The age of many rock units within the region is currently poorly understood and determining their age is critical for the development of a comprehensive geological model. Rock samples will be collected during the course of geological mapping. It is planned to collect several pounds of rock material from at least 16 sites. These sites will be determined once geologists have identified the key stratigraphic units and decide which are suitable for age dating. Preliminary sampling has been carried out this summer as part of the geological mapping and Lakehead University studies. This project is on-going.
6. Surficial Geochemistry: Initially planned as a one-year project was extended to a second year to allow for follow-up to the year one results. This project is studying the glacial history of 5 specific areas. Numerous PGE and nickel anomalies were revealed in regional lakes during the Ontario Treasure Initiative. The sources of these anomalies are puzzling to the prospectors that followed up the surveys. The objective is to classify the glacial materials and to create case histories of metal transportation in glacial and surficial drainage patterns. The result will be a better understanding of the concentration of metals in lake sediments in the area. It is expected that the results from this work will be published in April 2005.
7. Lakehead University Stratigraphic mapping and petrology studies: Lakehead University is a partner in the LNRGI (Metsaranta and Fralick, this volume; Richardson and Hollings, this volume). As part of our objective to provide local economic benefit, OPA is providing funding to Lakehead University to support the studies of geology students at the university. Much of this work will rely on diamond-drill core from various exploration sites in the region as well as stratigraphic mapping of vertical bedrock outcrops. Detailed sedimentary basin reconstruction and petrochemical differentiation of the mafic and ultramafic intrusions are essential components of the geological interpretation of the Nipigon region.
8. Geographic information system (GIS) compilations of legacy data are underway. This work will compile and index the current large volume of disparate data in the entire LNRGI area and will provide a base for further investigation and research. A large volume of proprietary in-kind data will be integrated with regional maps and databases under a common user-friendly format.
9. Geological Survey of Canada will undertake 2 projects in the Lake Nipigon region. Jim Carven is collecting magnetotelluric (MT) geophysical data, which will provide deep crustal profiles across the western edge of the Nipigon Embayment. Richard Ernst has carried out a paleomagnetic study of region dike swarms with the hope of providing insight to intrusive activities during the Proterozoic.
10. Diamond-drill core recovery: This is an on-going project of retrieving diamond-drill core from field locations and placing it in safe storage at the Conmee Township diamond-drill core storage site.
11. Lineament Study: This is a desk-top study to look at satellite imagery and airphotos to provide an analysis of the local and regional structures within the Lake Nipigon region study area.
12. Geophysical Modelling: It is anticipated that this project will study selective geophysical modelling over selected areas of interest.

PROGRAM DELIVERABLES

In addition to progress reports made by the geoscientists involved in the different projects at various Ontario Prospectors Association organized symposia in 2004, the following deliverables have been or will be released as part of the LNRGI program.

1. high-resolution airborne magnetic and gamma-ray spectrometry maps: April 2004
2. bedrock geology maps, at 1:50 000 scale, and reports for the western Nipigon Embayment: April 2004
3. detailed ground gravity maps with improved resolution: September 1, 2004
4. surficial geochemical case histories and recommended exploration methods
5. new age determinations for rocks in the Nipigon Embayment
6. digital and paper products from the GIS compilation
7. A regional summary and interpretation of the combined results will be delivered by the OGS and Lakehead University staff in subsequent years along with presentations and field excursions at the Institute on Lake Superior Geology (ILSG) conference in May 2005.

The deliverables will be published by the Ontario Geological Survey to ensure high standards of editing and consistent presentation and release of geoscience data.

ACKNOWLEDGMENTS

This project could not have advanced so far so rapidly without the efforts of all the industry collaborators, the staff of the Ministry of Northern Development Mines (OGS Precambrian Geoscience Section, Resident Geologist Program, and Publication Services Section), the LNRGI Science Advisory Committee, and Implementation Committee, especially the chairpersons of each committee and the administration staff of the Ontario Prospectors Association. Finally, this program would not have happened without the funding from the Northern Ontario Heritage Fund Corporation.

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48. Project Unit 03-001. Lake Nipigon Region Geoscience Initiative. Proterozoic and Archean Geology of the Southern Area of the Western Nipigon Embayment

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INTRODUCTION

The Lake Nipigon Region Geoscience Initiative (LNRGI) is funded through an agreement with the Northern Ontario Heritage Fund Corporation that is administered by the Ontario Prospectors Association (OPA) (Rayner, this volume). LNRGI also involves partnerships with the private sector, Lakehead University and several communities in the Lake Nipigon area. The aim of the initiative is to attract mineral industry investment to the Lake Nipigon area (Rayner, this volume, *see also* Figure 47.1) through bedrock mapping, airborne magnetic and gravity surveys, and targeted surficial geochemical and geochronological studies.

This project represents the second year of bedrock mapping of the western Nipigon Embayment at 1:50 000 scale (Rayner, this volume, *see also* Figure 47.1). Mapping of the southern map area has been completed by the Ontario Geological Survey as part of its commitment of in-kind support to the LNRGI, and focussed on area encompassing the southern Black Sturgeon River and Seagull Lake (Figure 48.1). This project also includes interpretation of igneous petrogenesis, stratigraphic analysis, and the development of geological cross-sections, to be undertaken in co-operation with the Lakehead University teams (e.g., Metsaranta and Fralick, this volume; Richardson and Hollings, this volume). In addition, this project will incorporate newly acquired airborne magnetic and gamma-ray data as well as ground gravity data (Rayner, this volume), and data acquired by re-logging of diamond-drill core. The LNRGI will also produce a comprehensive geoscience database that will assist mineral exploration for copper, nickel, platinum group elements (PGE) and copper-gold-rich mineralization.

ACCESS AND PREVIOUS WORK

The southern map area is located approximately 85 km northeast of Thunder Bay and north of Lake Superior. Access is provided by the Black Sturgeon Road, which extends north from highways 11 and 17 at Hurkett, the Dorion Cutoff Road which extends west from Dorion at highway 17 across to highway 527, and the numerous logging roads that branch off these two roads (*see* Figure 48.1). Previous geological mapping by Coates (1972) covered most of the map area at a scale of 1:63 360. The southern edge of the map area was previously mapped by McIlwaine and Tihor (1975a, 1975b) at 1:15 840 scale. Exploration in the early 1900s resulted in discovery of lead and zinc mineralization and limited production from the Dorion Mine in 1903 (Shklanka 1969). Discovery of copper mineralization near

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Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.48-1 to 48-11.

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Disraeli Lake, located north of the map area, in 1965 resulted in a surge in copper exploration activity in the late 1960s (Coates 1972). Exploration for uranium has been cyclical, with the greatest activity occurring in the middle to late 1970s coinciding with the discovery of large unconformity related deposits in other locations including the Wollaston Basin of Saskatchewan (Scott 1987). Exploration for PGE mineralization intensified around 1998. Mineralization is present in the Seagull–Leckie lakes intrusion in the northwest corner of the map area, and initial results indicated the presence of a basal pyroxenite hosting up to 1.71 ppm Pt and 1.87 ppm Pd over 2.1 m (Durham 2000). Work completed in early 2004 has also defined two zones higher in the intrusion with up to 1.52 ppm Pt and 1.78 ppm Pd over 3.0 m and 1.56 ppm Pt and 1.87 ppm Pd over 3 m in the upper and lower zones, respectively (East West Resource Corporation 2004).

GENERAL GEOLOGY

The map area is underlain by Archean rocks of the Quetico Subprovince that are unconformably overlain by Proterozoic sedimentary rocks and intruded by Proterozoic peridotite intrusions and diabase sills (*see* Figure 48.1). Rocks of the Quetico Subprovince consist of andalusite to biotite schists that are gradually replaced to the south by amphibolites, and these rocks are intruded by leucocratic granite dikes and bodies. The Archean rocks cut by a few widely spaced, north-trending mafic dikes. These units are unconformably overlain by the Proterozoic Sibley Group, which consists of relatively flat-lying muddy siltstones, sandstones, dolomites, and limestones of the Rossport Formation overlain by shales, siltstones, and sandstones of the Kama Hill Formation. Pyroxene peridotite intrusions, with olivine gabbro border phases, intrude the Archean rocks of the Quetico Subprovince and the sedimentary rocks of the Sibley Group, and are localized in the Seagull–Leckie lakes and central Hele Township areas. Proterozoic olivine diabase sills, up to 200 m thick, intrude all other units in the area and are chilled against the ultramafic intrusions.

Quetico Subprovince

Metamorphic rocks of the Quetico Subprovince are the dominant rock type east of the Black Sturgeon River, and there is a progressive increase in metamorphic grade from north to south. To the north, remnants of the sedimentary bedding are commonly evident in the andalusite and biotite schists, and primary differences in unit composition may control the distribution of andalusite rich units (Hart and Magyarosi 2004). Biotite schists are more common in the central portion of the area and are gradually replaced to the south by amphibolites that are relatively uniform in composition and occasionally intruded by dikelets of granite. Gneissic to migmatitic textures are relatively rare and are best developed in close proximity to the contact between the metamorphic rocks and felsic intrusive rocks. Interlayering of the metamorphic and felsic intrusive rocks is more common on the scale of tens of metres.

Felsic intrusive rocks are predominantly leucocratic granite with occasional biotite and hornblende granites and pegmatitic leucogranite. The granites occur as irregular-shaped bodies that are generally coarse-grained, massive to very weakly foliated, with biotite and muscovite constituting less than 2% of the rock that intrude, and may contain xenoliths of, the schists and amphibolites. Granite is the dominant rock type in the areas of southern Wolf Lake, south of Mound Lake, and east of the Black Sturgeon River and north of highway 17 and 11 (*see* Figure 48.1). In some localities, very coarse-grained to pegmatitic pods and dikelets are common in the granites and may contain tourmaline, or less commonly very coarse-grained magnetite, in areas intruded by pegmatitic leucogranite dikes. The best examples of magnetite-bearing pegmatite pods are located on Church Lake and in the southwest portion of the map area, west of the shaft of the Bishop Mine (*see* Figure 48.1).

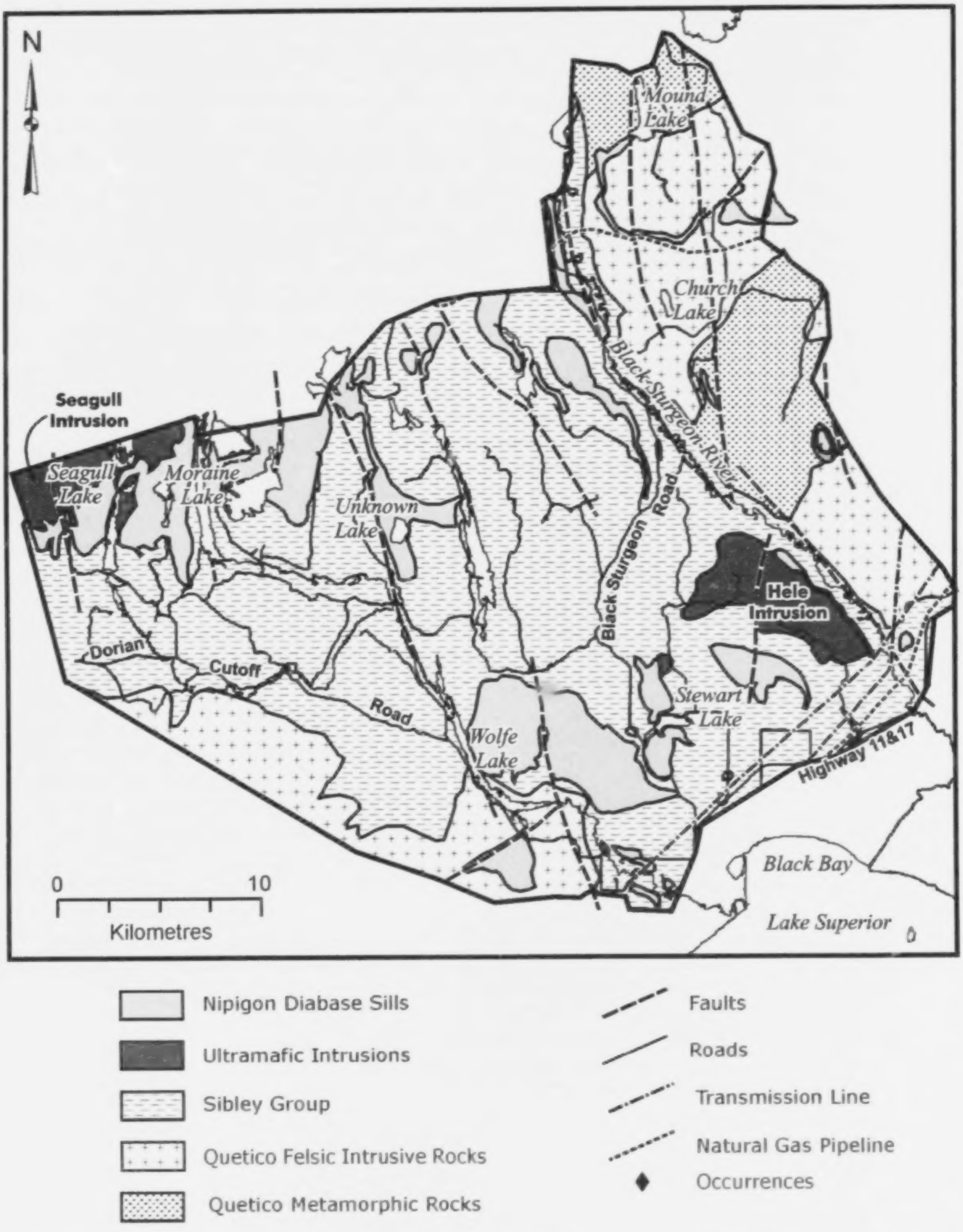
N
Mound Lake
Church Lake
Black Sturgeon River
Seagull Intrusion
Seagull Lake
Moraine Lake
Unknown Lake
Black Sturgeon Road
Hele Intrusion
Dorian
Cutoff
Road
Stewart Lake
Wolfe Lake
Highway 11&17
Black Bay
Lake Superior
0
10
Kilometres
Nipigon Diabase Sills
Ultramafic Intrusions
Sibley Group
Quetico Felsic Intrusive Rocks
Quetico Metamorphic Rocks
Faults
Roads
Transmission Line
Natural Gas Pipeline
Occurrences

Figure 48.1. Generalized geology of the map area, located approximately 85 km northeast of Thunder Bay between Lake Nipigon and Lake Superior.

In the northeast portion of the map area south of Mound Lake, dikes of pegmatitic muscovite leucogranite intrude the massive granites and andalusite and biotite schists, and constitute up to 30% of the outcrop (*see* Figure 48.1). The dikes range from less than 1 m to up to 10 m wide and may contain graphic intergrowths of tourmaline and quartz, plumose muscovite-quartz intergrowths, reddish brown garnet, minor amounts of light green mica, or rosy quartz. Although the dikes intrude the andalusite and biotite schists, they occur in close proximity to the massive leucogranite bodies.

Sibley Group

Proterozoic Sibley Group sedimentary rocks in the map area form a relatively flat-lying stratigraphic sequence consisting of the entire Rossport Formation overlain by the Kama Hill Formation (Cheadle 1986). The lower most unit of the Sibley Group varies with location as a result of tens of metres of topographic relief on the depositional paleosurface, as suggested by Cheadle (1986). In the area east of Wolf Lake, interbedded mudstones and sandstones, containing angular pebbles of Archean rocks, unconformably overlie rocks of the Quetico Subprovince. The youngest detrital zircon U/Pb age for a sandstone of the Pass Lake Formation is 1634 Ma, whereas 1450 Ma is the youngest U/Pb age for a sandstone of the Outan Island Formation, which overlies the Kama Hill Formation (L.M. Heaman, University of Alberta, personal communication, 2004). Although every member of the Rossport Formation and most of the Kama Hill Formation is present within the map area, exposure is generally limited to portions of the stratigraphy even within a single cliff exposure.

The majority of the Rossport Formation is composed of the Channel Island Member, which is overlain by the poorly exposed Middlebrun Bay and Fire Hill members. The lowest units are mudstones of the Channel Island Member, and these units are exposed in a number of scattered locations in the southwest portion of the map area. These units are overlain by interbedded mudstones and siltstones with occasional 0.5 to 1.0 cm thin pebbly sandstone beds best exposed to the west along the Dorion Cutoff Road (*see* Figure 48.1). The interbedded mudstones and siltstones are overlain by a series of cyclic mudstone and dolomite, with the best example exposed along the east shore of Wolf Lake under the diabase sill (*see* Figure 48.1). Most of the area north of the Dorion Cutoff Road and along the south-central portion of the map area consists of interbedded mudstone, siltstone and sandstone that overlie the cyclic mudstone. The sandstones thicken upward forming beds up to 30 cm thick, and these competent beds resulted in the formation of the Upper Falls on the Wolf River and Moraine Falls on Moraine Creek (*see* Figure 48.1). Sand injection dikes, with clasts of siltstone, cut the muddy siltstones in two locations and are interpreted to represent synsedimentary structures (P. Fralick, Lakehead University, personal communication, 2004). Outcrops of stromatolitic limestone of the Middlebrun Bay Member were observed in 2 locations, southwest of Moraine Lake and on the eastside of the Black Sturgeon River in southeast Hele Township (*see* Figure 48.1; Photo 48.1). Mudstones of the Fire Hill Member overlie the stromatolitic limestone, but are poorly represented in the map area with the possible exception of an exposure north of the Wolf River near highways 17 and 11 (R. Metsaranta, Lakehead University, personal communication, 2004). Intraformational conglomerates and/or debris flows containing clasts of Rossport Formation mudstone, siltstone, sandstone and minor mudstones of the Kama Hill Formation may mark the transition between the Rossport and Kama Hill formations. The best examples are exposed northwest of Wolf Lake and in south-central Hele Township.

Laminated mudstones and siltstones of the Kama Hill Formation, commonly overlain by diabase sill, are observed at higher elevations in the northern portion of the map area. In one location south of Unknown Lake (*see* Figure 48.1), outcrops of interbedded mudstone, siltstone and sandstone contain collapse breccias composed of blocks up to a few metres in diameter. This exposure has been interpreted to represent a pro-grade deltaic sequence, located towards the top of the Kama Hill Formation (P. Fralick, Lakehead University, personal communication, 2004).

Mafic to Ultramafic Intrusive Rocks

Ultramafic intrusions consisting of pyroxene peridotite with olivine gabbro and monzogabbro border phases occur in the Seagull Lake area in the northwest and the central Hele Township area in the southeast parts of the map area (*see* Figure 48.1). The intrusions cut Sibley Group and Quetico Subprovince rocks and are, in turn, cut by diabase sills. A preliminary U/Pb age of 1112.8±1.4 Ma, based on baddeleyite, was obtained recently from the olivine gabbro phase of the Seagull Intrusion (L.M. Heaman, University of Alberta, personal communication, 2004). Results from the Hele intrusion are pending. The peridotites are medium to coarse grained and massive, consisting of olivine and pyroxene with a variable feldspar content and 1 to 2% reddish brown mica. Generally poorly exposed, the peridotite usually contains numerous, subparallel serpentine-rich fractures and is deeply weathered resulting in a pebbly black sand regolith. In diamond-drill core, the peridotites have occasional ophitic intervals consisting of very coarse-grained pyroxene oikocrysts, with the best examples observed in the Seagull intrusion. Contacts between the peridotite and olivine gabbro observed in diamond-drill core are generally gradual transitions in grain size and olivine and plagioclase content.

The border phase of the ultramafic intrusions is composed of an irregularly distributed olivine gabbro that hosts irregular bands and pods of monzogabbro, or granophyre. Olivine gabbro is fine to medium grained and massive consisting of pyroxene, olivine and plagioclase. The olivine gabbro of the Seagull intrusion contains 1 to 2% reddish brown mica, but mica is much less abundant or absent in Hele intrusion. The monzogabbro is generally fine to medium grained and commonly resembles the olivine gabbro with pink feldspar, and is distinguished from the olivine gabbro by the occurrence of greater than 25% pink feldspar. Less commonly, the monzogabbro is very coarse grained and may contain fine-grained, massive reddish pink feldspar with minor quartz. This type of monzogabbro is present in both intrusions, but is much more common in outcrop in the Hele intrusion. The abundance of pink feldspar correlates with elevated K_2O values, and has been interpreted to be the result of the assimilation of Sibley Group sedimentary rocks (Hart and Magyarosi 2004).

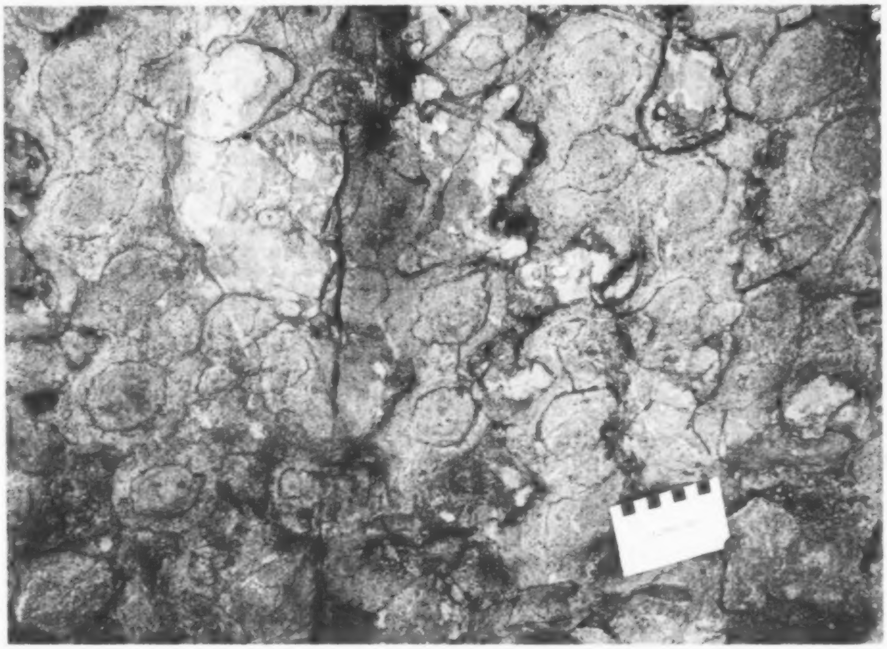

Photo 48.1. Stromatolitic limestone of the Middlebrun Bay Member, Sibley Group southwest of Moraine Lake.

Differences in the mineralogy and the volume of monzogabbro between the Seagull and Hele intrusions may be related to the size of the intrusions, as estimated from diamond-drill holes. The Seagull intrusion has a maximum thickness of 730 m and most of this thickness consists of the ultramafic rocks, whereas the Hele intrusion has a maximum thickness of 130 m and consists of a mixture of olivine gabbro and ultramafic rocks. However, the geochemistry for the Seagull and Hele intrusions indicates that the 2 intrusions are comparable to each other and to the Disraeli Intrusion (e.g., Hart 2004). However, these peridotites are geochemically different than the Kitto–Jackfish intrusions that included the Kitto intrusion in the Beardmore area, the Jackfish sills in the English Bay area, and the Ozone sills in the Kama Hill area (Hart 2004).

Diabase Sills

A series of generally flat-lying Proterozoic Nipigon diabase sills intrude all other rock units in the map area forming sills ranging in thickness from a few tens of metres to nearly 200 m. Diabase sills in the Muskrat Lake and Grand Bay areas have preliminary U/Pb ages of 1112.7±2.4 Ma and 1112.4±2.4 Ma, based on baddeleyite (L.M. Heaman, University of Alberta, personal communication, 2004). Although comparable in age to the 1112.8 Ma Seagull intrusion, diabase sills crosscut and are chilled against the ultramafic intrusions. The sills are usually composed of massive, medium- to coarse-grained feldspar and pyroxene, with trace to 3% fine-grained olivine and 1 to 2% magnetite. Medium- to coarse-grained diabase typically lacks a subophitic or diabasic texture and should properly be classified as gabbro, but, to avoid confusion, a diabase classification has been applied to all rocks associated with the sills. In a few locations, 2 distinctly separate sills have been identified that are separated by 0.30 to 20 m of Sibley Group sediment. There are few textural or mineralogical differences between the sills in these locations that could be used as stratigraphic markers on a map or regional scale. One exception is a sill located southwest of Moraine Lake (*see* Figure 48.1) that has an orbicular texture core with a chilled margin composed in part by densely packed fine orbs (Photo 48.2). Similar orbicular textures were not observed elsewhere in the map area, but are observed in a sill cut by drill hole NI92-7 located west of Disraeli Lake.

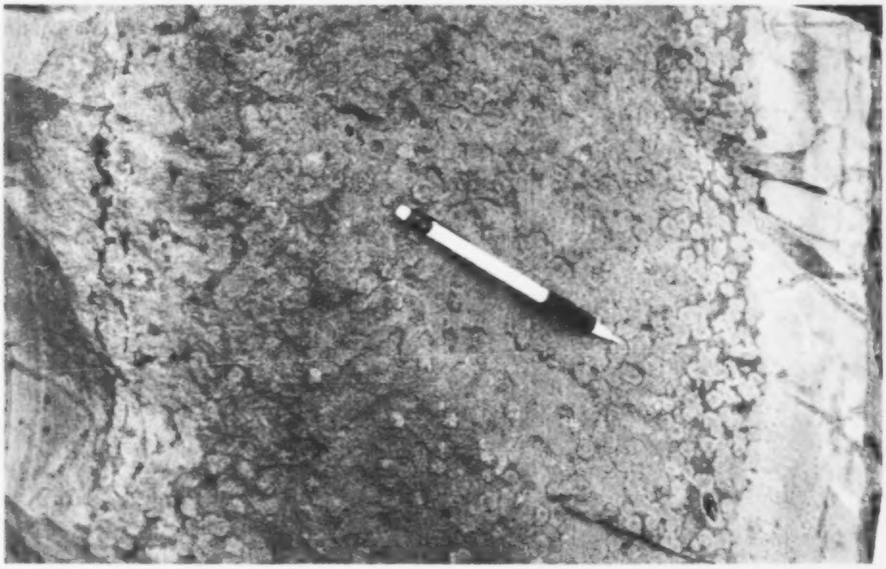

Photo 48.2. Orbicular-textured mafic sill intruding sedimentary rocks of the Rossport Formation of the Sibley Group southwest of Moraine Lake. The size of the pencil is approximately 15 cm.

The internal textural subdivisions, described by Sutcliffe (1986) and Hart and Magyarosi (2004), are not well defined in the map area, but are probably present as some of the individual textures and phases, such as pegmatitic, ophitic, and magnetite-rich, respectively, are exposed in the map area. Pegmatitic diabase is common toward the sill contacts and consists of irregular patches or dikes of very coarse-grained white to pink feldspar and amphibole with occasional pink feldspar. Ophitic textured diabase consists of pyroxene oikocrysts up to 2 cm in diameter and are observed in a few very fresh exposures, or very highly weathered exposures where the oikocrysts occur as pebbles. Magnetite-rich diabase is a field term that describes a diabase containing magnetite that is the same grain size as the silicate mineral phases, in contrast to a generally smaller grain size, and occurs toward the top of the sills.

There are two general types of sill contacts that have been classified as chill and inclusion-rich chill. The most common type is an aphanitic to plagioclase porphyritic or glomeroporphyritic chill, a few centimetres in thickness that usually has a polygonal joint pattern if observed in plan view. The chill zones are generally 2 cm wide and the grain size increases to medium to coarse grained over a distance of less than a metre. The inclusion-rich chill contact is relatively rare, and is characterized by a fine-grained, massive, biotitic diabase matrix containing angular to subangular pebble-sized xenoliths are composed of coarse-grained quartz and white to pinkish feldspar. Examples of the inclusion-rich chill are exposed on the west of the Black Sturgeon Road north of Stewart Lake, and north of Highway 17 and 11 west of the Black Sturgeon River (*see* Figure 48.1).

Structure

Archean rocks of the Quetico Subprovince are unconformably overlain by Proterozoic Sibley Group sedimentary rocks. Metamorphic rocks of the Quetico Subprovince have an approximately 060° schistosity and the felsic intrusive dikes generally follow the trend of the schistosity. Proterozoic Sibley Group sedimentary rocks dip from 5 to 10° with strikes that are oriented in a variety of directions. Some of this variation in strike azimuth may be the result of onlapping of the sediments onto local topographic highs in the Archean depositional surface (P. Fralick and R. Metsaranta, Lakehead University, personal communication, 2004) resulting in local variability. Regionally, the Sibley Group thickens to the southeast where two additional formations overlie the Kama Hill formation (Rogala 2003), and thins to the north and west (e.g., Cheadle 1986).

Proterozoic peridotite intrusions and Nipigon diabase sills intrude all older units in the map area. The Seagull intrusion appears to be lopolithic intruding along or close to the contact between the Quetico Subprovince and the Sibley Group. The Hele intrusion appears to be a sill, although there are few drill holes with which to constraint the geometry. It appears to have intruded into the Sibley Group sediments, which may be an explanation for the greater volume of monzogabbro compared to the Seagull intrusion. The diabase sills are generally flat lying, but in areas of greater exposure, such as the area burned by the 1999 forest fire in the Mound Lake area (*see* Figure 48.1), the shallowly dipping nature of many of the sills is evident. In the area immediately north of the natural gas pipeline, the diabase sill can be observed to dip shallowly to the north (Photo 48.3), whereas along the Black Sturgeon River, the same sill can be observed to dip shallowly east. The shallow inward-dipping orientation of this sill, forming a broad saucer, is also visible in the airborne magnetic pattern (Ontario Geological Survey 2004). On a smaller scale, the chill contacts of the sills are observed to dip shallowly in a variety of orientations across the map area.

There are two major regional fault trends that define the structural zone referred to as the Black Sturgeon fault, and a third trend representing pre-existing Archean structures (*see* Figure 48.1). A series of north-trending faults are interpreted to be regionally continuous structures and can be traced for over 50 km. These faults have been interpreted to be *en échelon* resulting in the formation of an asymmetric basin or graben as originally proposed by Coates (1972). Vertical displacements is variable, and there appears to have been little lateral displacement based on the correlation of the iron formations near the south end of Black Sturgeon Lake (Hart and Magyarosi 2004). The northwest offsets in the north-trending faults are interpreted to be a result of displacement along northwest-trending faults. The northwest faults are also evident in the topography and exposure of diabase in the map area. The northeast-trending faults are less well defined and appear to parallel the fabric of the Quetico Subprovince rocks. These faults appear to have some control over the distribution of the diabase sills, but it is not clear whether they had any control on the deposition of the Sibley Group.

Alteration

Intrusion of the peridotite or diabase into Sibley Group rocks results in the development of calc-silicate hornfels adjacent to the contact. The mudstones and siltstones form a light green, mauve, reddish grey to light grey banding composed of a tremolite- and carbonate-rich mineral assemblage. Dolomite-rich beds form white to buff marbles. The best example of hornfels is exposed in a rock-cut along the north side of highways 17 and 11, west of the Black Sturgeon River, where a block of Sibley sedimentary rocks is deformed by a diabase sill.

Hematite alteration, occurring as disseminated hematite and less commonly specular hematite, is sporadic and when present is commonly associated with late fracturing in both Archean and Proterozoic rocks. The hematization is generally associated with north-trending structures and may be a useful indicator of the presence of north-trending faults in areas with limited bedrock exposure.

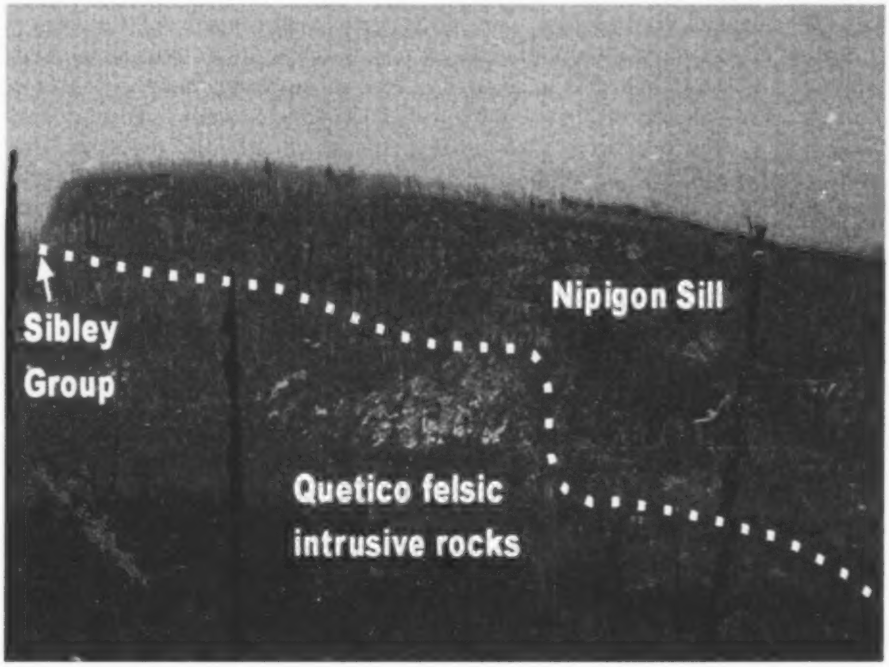

Photo 48.3. Approximate trace of the north- to northeast-dipping contact between the overlying Nipigon diabase sill and felsic intrusive rocks of the Quetico Subprovince, with a thin interval of Sibley Group sedimentary rocks located between these two units on the southwest side of the cliff. Photograph looking west in the area immediately north of the natural gas pipeline.

Mineralization

Platinum group mineralization in the Seagull intrusion is associated with sulphide minerals hosted by peridotite. Platinum group minerals are located at the grain boundaries of Ni-Fe-sulphide minerals, and are dominated by sperrylite, keithconnite, stibiopalladinite, and a copper palladium alloy (Heggie and Hollings 2004). Eighteen diamond-drill holes, totalling about 8328 m, have been completed in the Seagull intrusion to investigate the PGE mineralization. Mineralization is present in 3 units, basal, sub-main, and main, but it is most significant in the basal and sub-main units (Heggie and Hollings 2004). The basal pyroxenite hosts up to 1.71 ppm Pt and 1.87 ppm Pd over 2.1 m (Durham 2000). Recent work has outlined mineralization that may correlate with the sub-main and main units. The best results are up to 1.52 ppm Pt and 1.78 ppm Pd over 3.0 m and 1.56 ppm Pt and 1.87 ppm Pd over 3 m in the upper and lower zones, respectively (East West Resource Corporation 2004). Mineralization in the basal unit is interpreted to be a result of sulphur saturation of the magma during initial stages of emplacement and mineralization in the sub-main unit is associated with more primitive whole rock geochemistry and mineralogy possibly reflecting an influx of less evolved magma (Heggie and Hollings 2004).

Pegmatitic, muscovite leucogranite dikes intrude the metamorphic and felsic intrusive rocks of the Quetico Subprovince, with the highest concentration occurring in the area south of Mound Lake (*see* Figure 48.1). The presence of graphic intergrowths of tourmaline and quartz, the presence of reddish brown garnet and light green mica, and plumose muscovite-quartz intergrowths may indicate that these dikes are related to a fertile granite and, therefore, have the potential to host rare-element mineralization (Breaks, Selway and Tindle 2003). Further investigation of this area is warranted.

Bishop Mine is located in the same northeast-trending fault zone that hosts the Dorion Mine to the southwest. The fault zone cuts Archean granites and the overlying Proterozoic mudstones and siltstones, and contains a fault breccia with a carbonate and quartz matrix. Fragments in the breccia are subangular to subrounded and reflect the composition of the adjacent wall rock. Carbonate is a major component of the breccia matrix and is white, subhedral and coarse grained and appears to have crystallized in an open space. Quartz is clear to smoky occurring as euhedral crystals filling partially open spaces. Sphalerite is light yellow to greenish yellow occurring as 0.5 to 1.0 cm thick medium-grained bands close to the margins of the breccia zones. Exposure of the breccia is limited, but the sphalerite bands appear to be discontinuous. Galena occurs disseminated through the breccia carbonate matrix as euhedral, medium to coarse grains. Assay results from this occurrence are pending.

The Tessier–Williamson uranium occurrence is located in Hele Township along the eastside of the Black Sturgeon River. The occurrence is described by Scott (1987) as biotite-quartz-feldspar gneisses intruded by granitic pegmatites, and a grab sample returned 680 ppm U and 20 ppm Th.

RECOMMENDATIONS FOR EXPLORATION

Recent re-sampling of diamond-drill core from the Seagull intrusion has resulted in identification of a wider distribution of PGE mineralization (East West Resource Corporation 2004). These results would be consistent with the interpretation by Heggie and Hollings (2004) who proposed that PGE mineralization is the result of sulphur saturation of magma during both the initial stages of emplacement and during subsequent injections of primitive magma. If the other ultramafic intrusions also formed as a result of multiple pulses of magma, then any portion of an intrusion has the potential to host PGE mineralization if the magma was PGE enriched at the time of emplacement.

Mapping has identified an area of peridotite located to the southwest of the main body of the Hele intrusion. The existence of peridotite outside the area previously defined as the limits of an ultramafic intrusion suggests that there is the potential for additional unidentified intrusions in the Nipigon Embayment. Additional work is required integrating the results of the airborne magnetic and gamma ray surveys with the ground gravity and geological mapping in an attempt to identify other potential targets.

The significance of the magnetite-rich pegmatite dikes in some of the granite bodies of the Quetico Subprovince is not understood. These dikes appear to be restricted to a few zones, one of which underlines the area of the Bishop Mine. Further investigation of the origins of these dikes is required.

Pegmatitic, muscovite leucogranite dikes in the Mound Lake area occur along a regional trend extending from Georgia–Barbara lakes area in the northeast to the DeCourcey Lake and Onion Lake areas in the southwest (Breaks, Selway and Tindle 2003) and, consequently, this area may contain a similar concentration of fertile granites. The abundance of dikes in this area, and the fact that these dikes have been examined in only a cursory manner during the mapping program suggests that additional prospecting is needed in the area south of Mound Lake (*see* Figure 48.1).

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49. Project Unit 03-304. Lake Nipigon Region Geoscience Initiative. Preliminary Results of Mapping in the West-Central Nipigon Embayment

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INTRODUCTION

The Lake Nipigon Region Geoscience Initiative (LNRGI) is funded through an agreement with the Northern Ontario Heritage Fund that is administered by the Ontario Prospectors Association (Rayner, this volume). LNRGI also involves partnerships with the private sector, Lakehead University, the Ontario Geological Survey (OGS), and several communities in the Lake Nipigon area. The aim of the initiative is to attract mineral investment to the Lake Nipigon area (Rayner, this volume, Figure 47.1) through bedrock mapping, airborne magnetic and gravity surveys, and targeted surficial geochemical and geochronological studies.

A two-year program of bedrock mapping, at a scale of 1:50 000, of the western Nipigon Embayment began in June 2003, as part of the LNRGI. Mapping of the southwestern (Hart and MacDonald 2003; Hart and Préfontaine 2004a, 2004b; Hart and Magyarosi 2004a, 2004b) and southern (Hart, this volume) areas of the Nipigon Embayment will be completed by the Ontario Geological Survey (OGS) as part of its commitment of in-kind support to the LNRGI (Rayner, Lane and Easton 2003). Mapping of the northern (Hart and MacDonald 2003; MacDonald et al. 2004a, 2004b; MacDonald and Tremblay 2004a; MacDonald 2004a) and west-central (2004 field season) map areas is conducted under a contract agreement with the OPA (Rayner, Lane and Easton 2003). This report includes the field observations and preliminary results of bedrock mapping conducted in 2004 in the west-central part of the Nipigon Embayment (Figure 49.1).

ACCESS AND PREVIOUS WORK

The west-central map area is located approximately 150 km north of Thunder Bay and west of Lake Nipigon (*see* Figure 49.1). Access is provided by Highway 527, an excellent network of logging roads and all-terrain vehicle (ATV) trails extending east and west of the highway, as well as many lakes and rivers. Previous work in the map area was conducted by Sage et al. (1974) at a scale of 1:126 720. Sutcliffe (1986) completed geological investigations of the diabase sills. Bedrock mapping of the shore of Lake Nipigon and adjacent areas, at a scale of 1:50 000, was conducted by Sutcliffe (1982a, 1982b). Mapping by Hart (2001) in the Garden Lake greenstone belt and Hart, MacDonald and Lepine (2001a, 2001b) in the Heaven Lake and Lac des Iles greenstone belts adjoins the west-central and southwestern map boundaries of the 2004 map area.

Summary of Field Work and Other Activities 2004, Ontario Geological Survey, Open File Report 6145, p.49-1 to 49-18.

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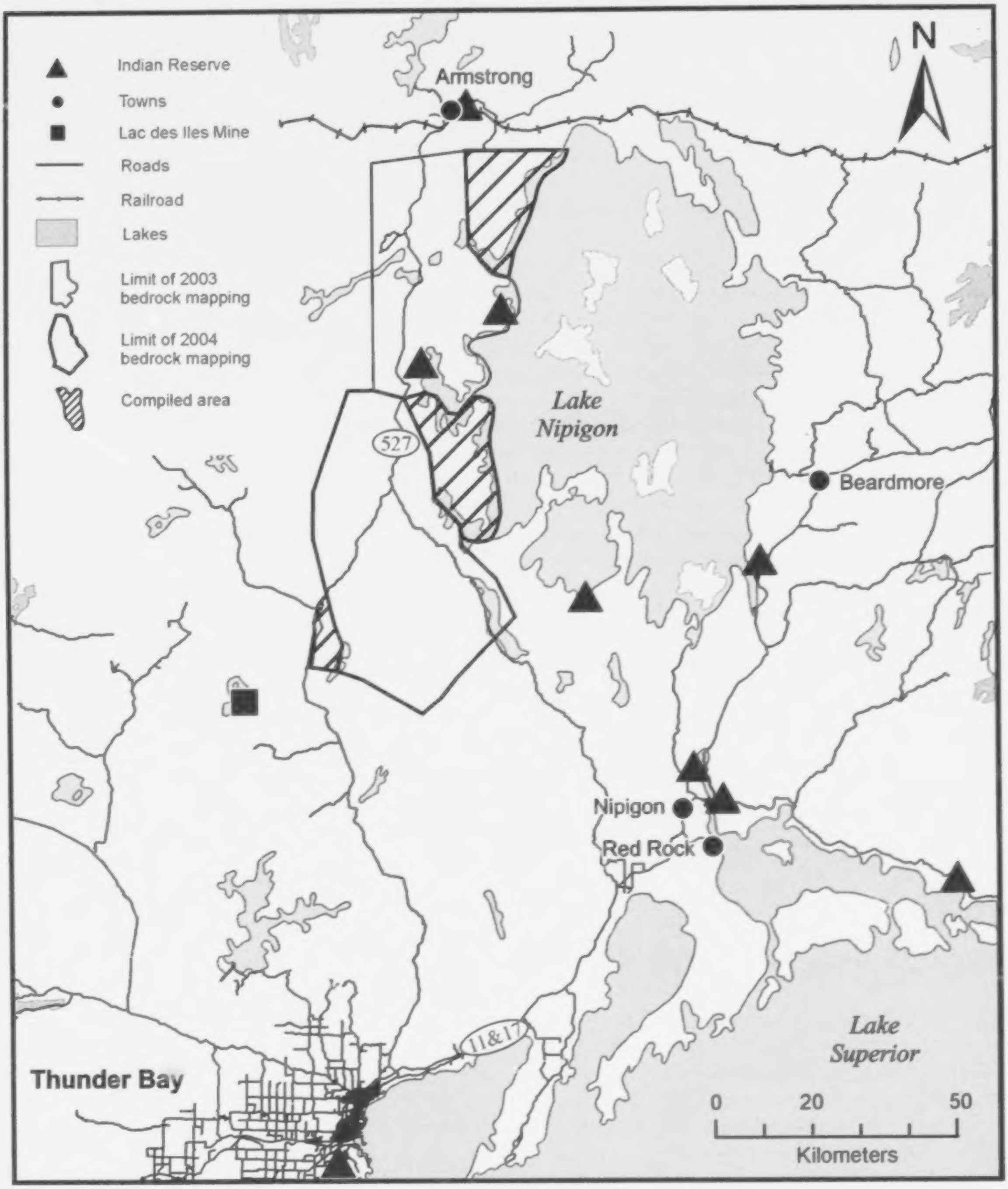
Indian Reserve
Towns
Lac des Iles Mine
Roads
Railroad
Lakes
Limit of 2003 bedrock mapping
Limit of 2004 bedrock mapping
Compiled area
N
Armstrong
Lake Nipigon
527
Beardmore
Nipigon
Red Rock
Thunder Bay
11&17
Lake Superior
0
20
50
Kilometers

Figure 49.1. Lake Nipigon region, showing the location of the 2003 and 2004 bedrock mapping projects funded by the Lake Nipigon Region Geoscience Initiative.

GENERAL GEOLOGY

Overview

The west-central map area covers 1800 km^2 and extends from just south of Gull River to approximately 4 km south of Little Muskrat Lake. The eastern boundary extends roughly southeast for 55 km through Chief Bay and east of Black Sturgeon Lake with the southeastern map boundary corresponding to the limit of mapping achieved by Hart and Préfontaine (2004a). The western boundary extends roughly south for 60 km along the west side of Cheeseman Lake toward Poshkokagan Lake. An additional 200 km^2 area (the Max–Mawn Lakes area) was mapped by R.M. Easton during the 2004 field season as part of the OGS contribution to the LNRGI. This area was completed to fill in gaps between the 2003–2004 LNRGI mapping projects and previous mapping in the Heaven Lake and Lac des Iles greenstone belts by Hart and MacDonald (2000a, 2000b), as well as mapping in the Max Lake area by Pye (1965). Data from the in-kind mapping and compilation of the Max–Mawn lakes area will be included in the final publications resulting from this LNRGI project.

The west-central map area is underlain by Archean granite, greenstone and metasedimentary rocks of the Wabigoon Subprovince that are unconformably overlain by Proterozoic sedimentary rocks and is intruded by Proterozoic diabase sills (Figure 49.2). Nipigon diabase sills account for 75 to 80% of the rocks within the map area.

Archean

METAVOLCANIC ROCKS

Archean metavolcanic rocks occur in 3 main parts of the map area:

1. 10 km west of Kabitotikwia Lake
2. the area south, north west and north of Poshkokagan Lake
3. several local areas within the 200 km^2 southwest map area (along strike with the metasedimentary rocks)

Mafic metavolcanic rocks crop out along relatively new logging roads in the area west of Kabitotikwia Lake. Outcrops consist mainly of variably foliated, pillowed flows with some massive flows, minor vesicular pillow fragment breccia and possible interflow iron formation (Photo 49.1a). The geographic position of this 7 km^2 Archean inlier, as well as the rock types present, suggests that it is a part of the Garden Lake greenstone belt (Hart 2001).

Metavolcanic outcrops in the Poshkokagan Lake area occur near the southern and northern ends of the lake. Outcrops at the north end of Poshkokagan, and along the shores of adjacent Lever Lake, consist dominantly of moderate to strongly foliated felsic to intermediate tuffs with sparse 3 mm diameter quartz crystal lapilli. Locally, the tuffs also contain vesicle-rich beds 0.5 to 1 m wide. Outcrops of variably foliated gabbroic amphibolite, interpreted to represent the margin of the Heaven Lake greenstone belt (Hart, MacDonald and Lepine 2001a), also occur north of Lever Lake. These outcrops form part of the Whistle assemblage (Hart and MacDonald 2000a; 2729 Ma: Tomlinson et al. 2004) of the Heaven Lake greenstone belt.

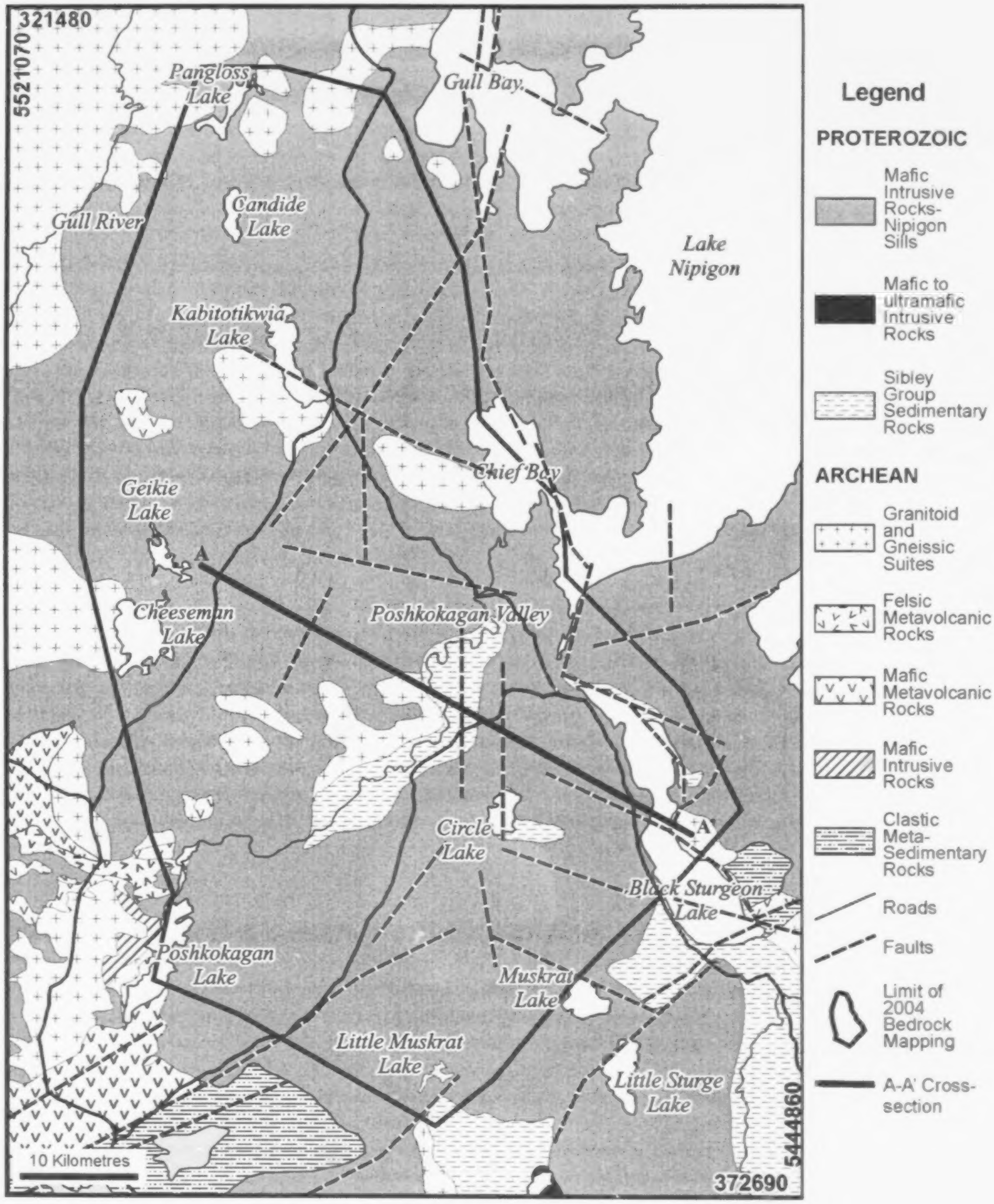
321480
5521070
Pangloss Lake
Gull Bay
Candide Lake
Gull River
Lake Nipigon
Kabitotikwia Lake
Chief Bay
Geikie Lake
A
Cheeseman Lake
Poshkokagan Valley
Circle Lake
A'
Black Sturgeon Lake
Poshkokagan Lake
Muskrat Lake
Little Muskrat Lake
Little Sturge Lake
10 Kilometres
5444860
372690
Legend
PROTEROZOIC
Mafic Intrusive Rocks-Nipigon Sills
Mafic to ultramafic Intrusive Rocks
Sibley Group Sedimentary Rocks
ARCHEAN
Granitoid and Gneissic Suites
Felsic Metavolcanic Rocks
Mafic Metavolcanic Rocks
Mafic Intrusive Rocks
Clastic Meta-Sedimentary Rocks
Roads
Faults
Limit of 2004 Bedrock Mapping
A-A' Cross-section

Figure 49.2. Simplified geological map of the west-central map area. Cross section A–A′ is shown in Figure 49.5.

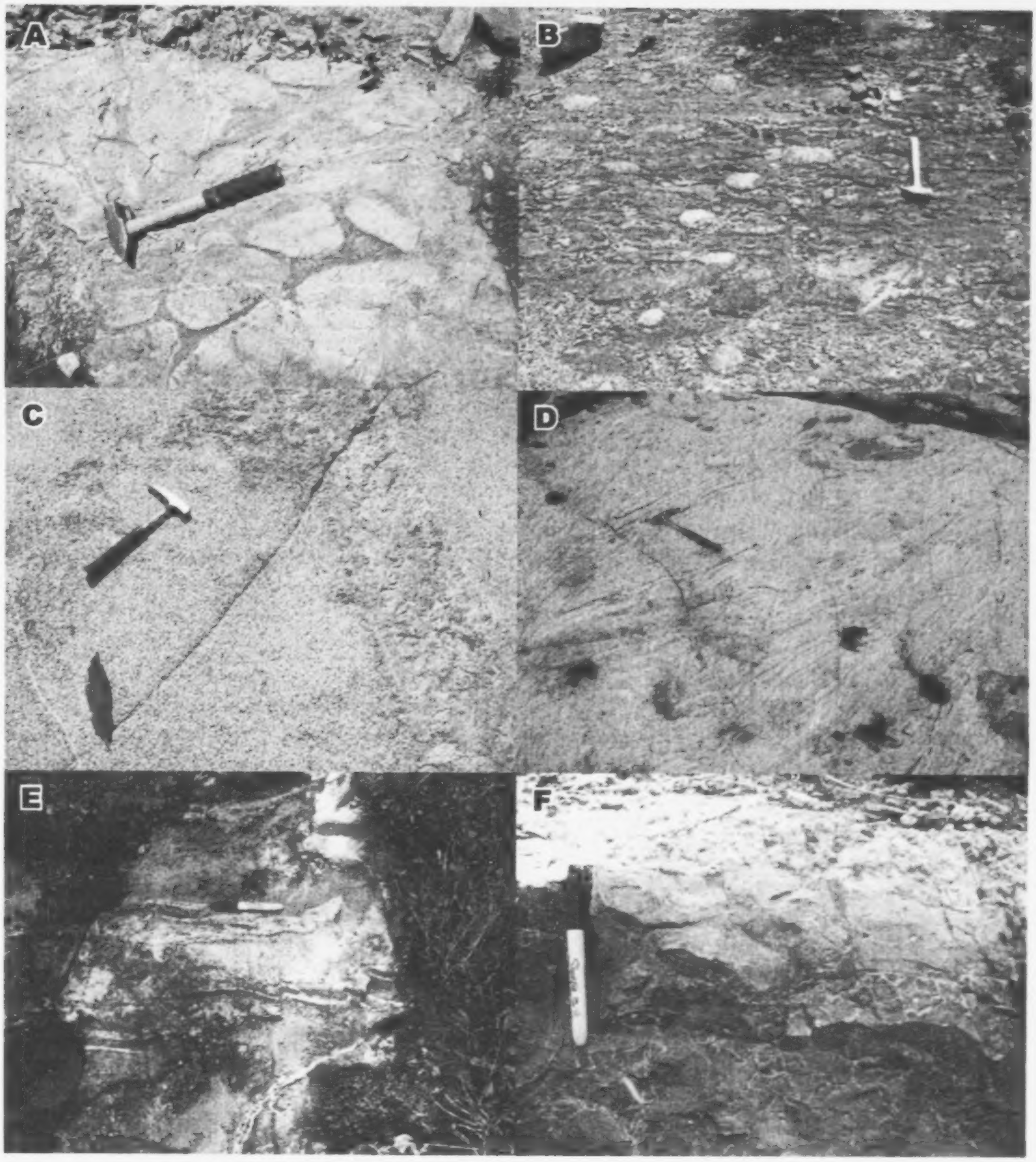

Photo 49.1. Photographs of the geology from west-central Nipigon Embayment.

A) Archean pillowed flow, southwest of Kabitotikwia Lake (UTM 330194E 5494059N, NAD 83, Zone 16).

B) Archean polymictic cobble conglomerate, southeast of Stucco Lake (UTM 339748E 5450373N, NAD 83, Zone 16).

C) Biotite granite containing amphibolite xenolith and crosscut by pegmatitic dike, north of Poshkokagan River (UTM 349434E 5475080N, NAD 83, Zone 16).

D) Rocks of the gneissic suite, east shore of Black Sturgeon Lake (UTM 364598E, 5469251N, NAD 83, Zone 16).

E) Paragneiss, gneissic suite, Chief Bay Island (UTM 353364E 5490362N, NAD 83, Zone 16).

F) Sibley Group hornfels (top) intruded by chilled diabase sill (bottom), north of Little Poshkokagan Lake (UTM 342200E 5476884N, NAD 83, Zone 16).

Outcrops of both mafic and felsic metavolcanic rocks occur along the west-central and southwest shores of Poshkokagan Lake. Dominant rock types are massive mafic volcanic flows with local mafic tuff to lapilli tuffs. Mafic lapilli tuffs typically contain exotic granitoid lapilli as well as siltstone to fine tuff lapilli-sized fragments. Felsic tuff beds of indeterminate thickness also occur interbedded with the mafic metavolcanic rocks and are characterized by their quartz crystal content, which ranges from 10 to 50%. These units represent parts of the northern margin of the Lac des Iles greenstone belt (Hart, MacDonald and Lepine 2001a, 2001b).

Archean metavolcanic rocks in the 200 km^2 Max–Mawn lakes area occur as 2 or 3 northeast-trending panels that are present within a dominantly siliciclastic metasedimentary sequence (Pye 1968; Kaye 1969; this report). The two northern metavolcanic panels each range from 300 to 500 m thick and possibly merge into one another (Max Lake panel) toward the east, north of Geddes Lake (Pye 1968). A southern panel occurs in the vicinity of Peevy Lake. Dominant rock types in both panels are massive to pillowed mafic volcanic flows, with minor mafic volcanic and intermediate volcanic-derived sandstone and mudstone. Volcanic-derived metasedimentary rocks occur at the north and south contacts of the Max Lake panel, and represents a transition from a volcanic to a sedimentary environment. It is possible that units in the Max Lake panel are repeated due to an anticline. Two isolated outcrops of moderately foliated to sheared amphibolite, located approximately 1.5 km southeast of Little Max Lake, could represent metamorphosed mafic volcanics near the margin of the Peevy Lake volcanic panel.

METASEDIMENTARY ROCKS

Archean metasedimentary rocks are present only within the 200 km^2 Max–Mawn lakes area. This area forms part of a 10 to 20 km wide continuous belt of metasedimentary and metavolcanic rocks that extends from Max Lake south to DeCourcey Lake. A deformation zone along Max Creek, which can be traced at least 10 km east of Highway 527, approximates the southern contact of the Lac des Iles greenstone belt. This metasediment-dominated belt is bounded to the south, near DeCourcey Lake, by Quetico Subprovince felsic intrusive and metasedimentary rocks (T.R. Hart, OGS, personal communication, 2004). Adjacent to the study area, metamorphic grade in the metasedimentary rocks is low, and ranges from low to middle greenschist facies.

The Archean metasedimentary rocks generally consists of thick-bedded metawacke, metasiltstone and metamudstone, with minor interlayered mafic to intermediate metavolcanic rocks. As noted under "Metavolcanic Rocks", the larger areas of metavolcanic rocks have been grouped into volcanic panels. Locally, particularly near contacts with the volcanic panels (Max Lake volcanic panel), the amount of mudstone within the sedimentary sequence appears to increase.

A package of metaconglomeratic and meta-arenaceous rocks, up to 2 km wide, occurs in a synformal structure lying just south of Max Creek, adjacent to the contact with the Lac des Iles greenstone belt. Dominant rock types are polymictic cobble to boulder metaconglomerate, ranging from sparse to densely packed, as well as medium-grained metawacke and medium-grained, locally cross-bedded, meta-arenite. Densely packed, polymictic cobble and boulder metaconglomerate is most abundant along the greenstone belt contact, and is best exposed on Highway 527 at Max Creek. This unit, can be traced east-northeast for roughly 7 km, and mylonitic rocks related to the greenstone belt contact can be traced another 3 km further east, where they occur as rafts in Nipigon diabase sill contacts, or as small outliers between diabase sills. A similar conglomerate also is exposed in outcrops southeast of Stucco Lake (Photo 49.1b). Although the densely packed metaconglomerate superficially resembles a "Timiskaming-type" metaconglomerate, it can be observed in outcrop grading into both meta-arenite and matrix-rich metaconglomerate. Thus, if the densely packed metaconglomerate is of "Timiskaming" affinity, then so is the entire package of metaconglomerate and meta-arenite present between the deformation zone along

Max Creek and the northern margin of the Max Lake volcanic panel. Percival and Sullivan (1988) reported a U/Pb age of 2687±3 Ma from a tonalite cobble from the Max Creek metaconglomerate. This age is a maximum age for deposition.

Overall, the geometry, composition and deposition of the metavolcanic and metavolcanic panels south of Max Creek resembles that observed along he southern margin of the Beardmore–Geraldton greenstone belt located east of Lake Nipigon (e.g., Williams and Stott 1991; Hart, terMeer and Jolette 2002; Tomlinson et al. 1998), particularly the presence of a northern conglomerate unit containing cross-bedded arenites and the alternation of metasedimentary and metavolcanic-dominated panels, with the abundance of metasedimentary rocks increasing to the south. If this comparison is valid, than the deformation zone along Max Creek may represent the eastward continuation of either the Paint Lake or Barton Bay deformation zones.

FELSIC TO INTERMEDIATE INTRUSIVE ROCKS

Biotite Granite Suite

Felsic to intermediate intrusive rocks form the bulk of Archean exposures in the west-central map area. Archean inliers of this type occur in 3 main areas:

1. west-southwest Kabitotikwia Lake
2. west Poshkokagan River valley
3. the east-central shore of Black Sturgeon Lake (*see* Figure 49-2)

In all 3 areas, rocks of the biotite granite suite are the dominant rock type. Outcrops are typically light to medium pink, and typically consist of coarse-grained, moderately to strongly foliated, biotite granite to monzogranite. Locally, outcrops may tend toward more medium-grained and granodioritic compositions. Angular to rounded, 3 to 40 cm long, amphibolite to hornblende diorite xenoliths are common (Photo 49.1c) as are 10 to 100 cm wide potassium feldspar-rich pegmatite dikes that locally contain magnetite. Light to medium pink, 2 to 100 m wide, aplite dikes that crosscut both the granite and pegmatitic dikes are also common.

Outcrops of the biotite granite suite in the Poshkokagan River valley area form a topographic high which may be representative of an original Archean paleotopographic high. Alternatively, the topographic high may be due to vertical offset along one of the many Proterozoic-age faults in the area (*see* Figure 49.2).

Gneissic Suite

Gneissic suite rocks are characterized by their strong foliation and heterogeneous layered nature. In the west-central map area, these rocks are typically associated with the biotite granite suite, particularly in the area east of Black Sturgeon Lake (Photo 49.1d). Overall composition of gneissic suite rocks in this area is similar to that observed in the biotite granite suite. More mafic layers in the gneiss are very thinly layered (<3 cm) and are typically only 2 to 30 mm wide. Amphibolite and layered amphibolite xenoliths, similar to those observed in the biotite granite suite, are also common in this unit (*see* Photo 49.1d). Contacts between rocks of the biotite granite and gneissic suites in the Black Sturgeon Lake area show ambiguous contact relationships, and may be gradational. A single outcrop on an island on the west side of Chief Bay contains grey to light grey, layered paragneiss (Photo 49.1e), that is cut by coarse-grained to pegmatitic dikes of the biotite granite suite.

Proterozoic

SIBLEY GROUP SEDIMENTARY ROCKS

Sibley Group sedimentary rocks occur in 4 main areas within the west-central map area:

1. the Black Sturgeon Lake area
2. the Poshkokagan River valley
3. a small area approximately 2 km east south east of Circle Lake
4. Chief Bay and Black Sturgeon Bay of Lake Nipigon (*see* Figure 49.2)

Outcrops of the Sibley Group in the Black Sturgeon Lake area generally consist of light beige to buff siliceous, well-sorted sandstone to siltstone. Local areas, limited in extent, of feldspathic sandstone or granule to pebble conglomerates occur toward the south. Locally, limestone may occur interbedded with siltstone to mudstone.

Sibley Group outcrops in the Poshkokagan River valley, generally consist of greenish to light greenish grey siliceous to calcareous siltstone that lie unconformably on rocks of the biotite granite suite. East-southeast of Circle Lake, several outcrops contain the only stromatolitic limestones observed in the west-central map area. Red to maroon muddy siltstone of limited areal extent also occurs proximal to the stromatolitic unit, either a few metres stratigraphically above or below the limestone.

Along the shores of Lake Nipigon, Sibley Group outcrops locally occur at the base of Nipigon diabase ridges. These outcrops range from light yellow green limestone on the east side of Chief Bay to more arenaceous siltstone and sandstone, with local clast-supported polymictic pebble to cobble conglomerate, along the shores of Black Sturgeon Bay. Some Sibley Group outcrops along Tchiatang Bluff in Black Sturgeon Bay are atypically oriented, striking west-southwest and dipping 75° to the northwest. This subvertical orientation of Sibley Group strata may be due to rotation of the beds upon intrusion of the Nipigon diabase sill. Calcareous outcrops along Chief Bay may have originally been stromatolitic limestone, with the primary stromatolites obliterated during contact metamorphism related to the adjacent Nipigon diabase sills.

Additional sparse outcrops of light yellow to light yellow green calcareous mudstone, light yellow to whitish calcareous siltstone, as well as non-calcareous sandstone to siltstone occur locally at the base of Nipigon diabase ridges throughout the map area. Hornfelsed Sibley Group sedimentary rocks are also commonly observed as a thin crust on top of (Photo 49.1f), and as inclusions in Nipigon diabase chill margins. Proximal to these contacts, potassium feldspar, chlorite, and hematite alteration types are common in both the Sibley Group sedimentary rocks and in the adjacent Nipigon diabase sills.

NIPIGON DIABASE SILLS

Nipigon diabase sills intrude and overlie 75 to 80% of the rocks within the map area. Davis and Sutcliffe (1985) reported a combined U/Pb age of $1109\ ^{+4}/_{-2}$ Ma from baddeleyite and zircon obtained from 2 sills in the Nipigon Embayment. This age is similar to that of the oldest Osler Group volcanic rocks, which are part of the Keweenawan Supergroup of the Midcontinent Rift. Preliminary U/Pb baddeleyite ages of 1110±3, 1113±2, 1112±5 Ma from diabase sills at Havoc, Muskrat Lake and Grand Bay, respectively (L.M. Heaman, University of Alberta, written communication, 2004), are within error of the previous age estimate by Davis and Sutcliffe (1985), and suggest relatively rapid emplacement of the Nipigon sills.

The Nipigon diabase sills are generally brown to grey-brown, massive, medium-grained intergranular-textured and gabbroic in composition. Local variations include fine- and coarse-grained with medium- to coarse-grained varieties commonly displaying ophitic and poikilitic textures (Photo 49.2d). A magnetite-rich phase also occurs in medium- to coarse-grained sills, and contains greater than 5%, intergranular to locally glomeroporphyritic, magnetite. A less common trachytoid texture may be present locally within the Nipigon diabase and is marked by a distinctive parallel alignment of plagioclase crystals. Textural and compositional variation in the Nipigon diabase sills is most marked proximal to contacts with Sibley Group sedimentary rocks. Textural and compositional variations include medium- to coarse-grained pods and veins, which are slightly more leucocratic than the hosting diabase (Photo 49.2a). Monzogabbroic, potassium feldspar-rich or inclusion-rich versions of the diabase may also occur proximal to contacts (Photo 49.2e). This is thought to possibly represent a late magmatic phase of the sills or assimilation of Sibley Group sedimentary rocks, or a combination of the 2 processes (Hart and Magyarosi 2004a) (Photo 49.2f). Sutcliffe (1986) subdivided the sills into ideal textural and mineralogical stratigraphic sections, but this "ideal" section is rarely observed in this map area, nor was it commonly observed in the 2003 map areas (MacDonald 2004a; Hart and Magyarosi 2004a).

Geochemistry

Preliminary geochemistry from some of the samples collected during the 2004 field season suggests that there may be 2 distinct groups of diabase in the west-central map area (Figure 49.3 and 49.4). None of the diabase samples analyzed to date from the 2004 map area plot in the field identified for the Inspiration sills (MacDonald and Tremblay 2004b); thus, it appears that the extent of the Inspiration sills is restricted to the northeast part of the 2003 northern LNRGI map area. Most diabase samples collected from the west-central map area have trace element characteristics similar to the "typical" Nipigon diabase sills identified in the northern map area (MacDonald 2004b; MacDonald and Tremblay 2004b). However, a group of 16 "visually typical" diabase samples from the Voltaire, Penny and Kabitotikwia lakes area have trace element characteristics similar to those of the olivine gabbro Jackfish Island sill (MacDonald 2004a; MacDonald and Tremblay 2004b, 2004c). Two other "visually typical" diabase samples collected in 2003 from the Pike Bay Peninsula in Gull Bay also plot in the field identified for the Jackfish Island sill (*see* Figure 49.3 and 49.4). These Jackfish-like diabase samples may represent a third type of diabase in the Nipigon Embayment. When compared to trace element signatures of other mafic to ultramafic intrusions in the Nipigon Embayment, the Jackfish Island and Jackfish-like samples may be chemically similar to the Kitto intrusion (*see* Figure 49.3 and 49.4) (Hart 2003).

Table 49.1 presents the average major element data for each of the possible mafic sill types in the western Nipigon Embayment. Inspiration, Nipigon and the Jackfish-like diabase samples all have similar major element contents, although TiO_2 is slightly elevated in the Jackfish-like diabase samples (*see* Table 49.1). Average major elements for the 2003 Jackfish suite samples have elevated MgO, and Fe_2O_3, and lower CaO and Al_2O_3 in comparison to the averages of the Inspiration, Nipigon and Jackfish-like diabase samples (*see* Table 49.1).

Geochemical data from the Pangloss, Geikie, Candide, Johnspine, and Lake Nipigon areas have not been received yet, so the geographic extent of other chemical sill types is unclear.

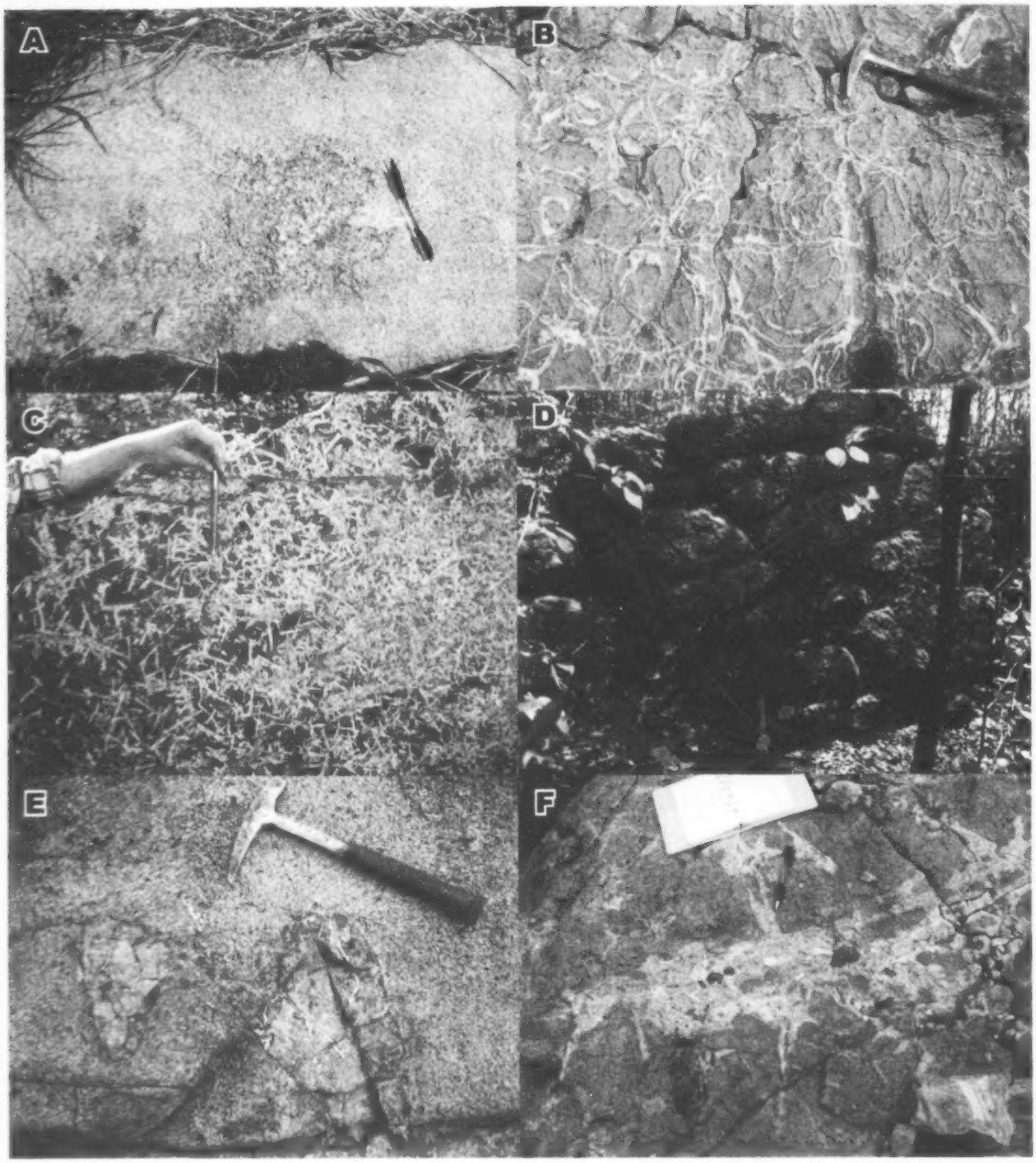

Photo 49.2. Photographs of the Nipigon diabase sills from the map area.

A) Amphibole-rich coarse-grained diabase pod within medium-grained diabase, northwest Black Sturgeon Lake (UTM 357428E 5476770N, NAD 83, zone 16).

B) Diabase chill margin with circular cooling features (perlitic cracks), east shore of Black Sturgeon Lake (UTM 364403E 5474427N, NAD 83, zone 16).

C) Joint surface in Nipigon sill filled with tremolite or wollastonite. Highway 527 east of Cheeseman Lake (UTM 335022E 5482870N, NAD 83, zone 16).

D) Oikocrystic and/or ophitic diabase with regular jointing pattern, west of Circle Lake (UTM 349041E 5468847N, NAD 83, zone 16).

E) Inclusion-rich monzonitic diabase (granophyric?), east of Black Sturgeon Lake (UTM 366760E 5469259N, NAD 83, zone 16).

F) Potassic alteration or aplitic material within medium-grained diabase located proximal to Sibley Group contact, east of Little Muskrat Lake (UTM 350747E 5452746N, NAD 83, zone 16).

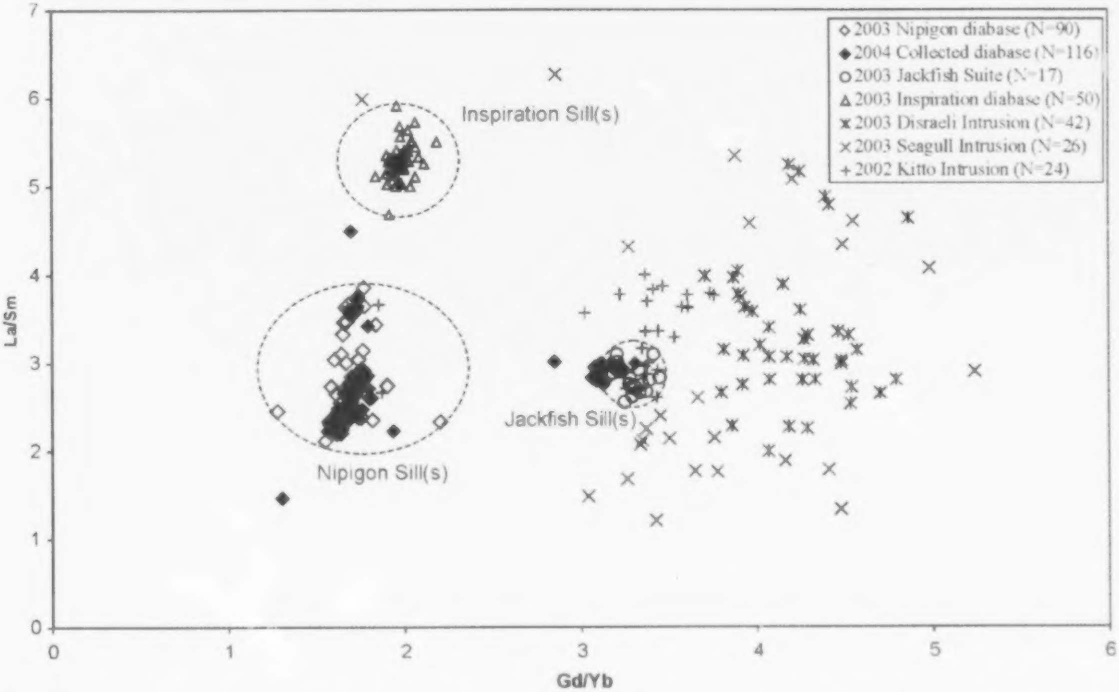

Figure 49.3. La/Sm versus Gd/Yb for samples from the Nipigon Embayment. Data sources are 2003 Nipigon diabase and Inspiration diabase (MacDonald and Tremblay 2004b); Jackfish Suite (MacDonald and Tremblay 2004b; Hart and Magyarosi 2004b); Disraeli and Seagull intrusions (Hart and Magyarosi 2004b); Kitto intrusion: (Hart, Jolette and terMeer 2002).

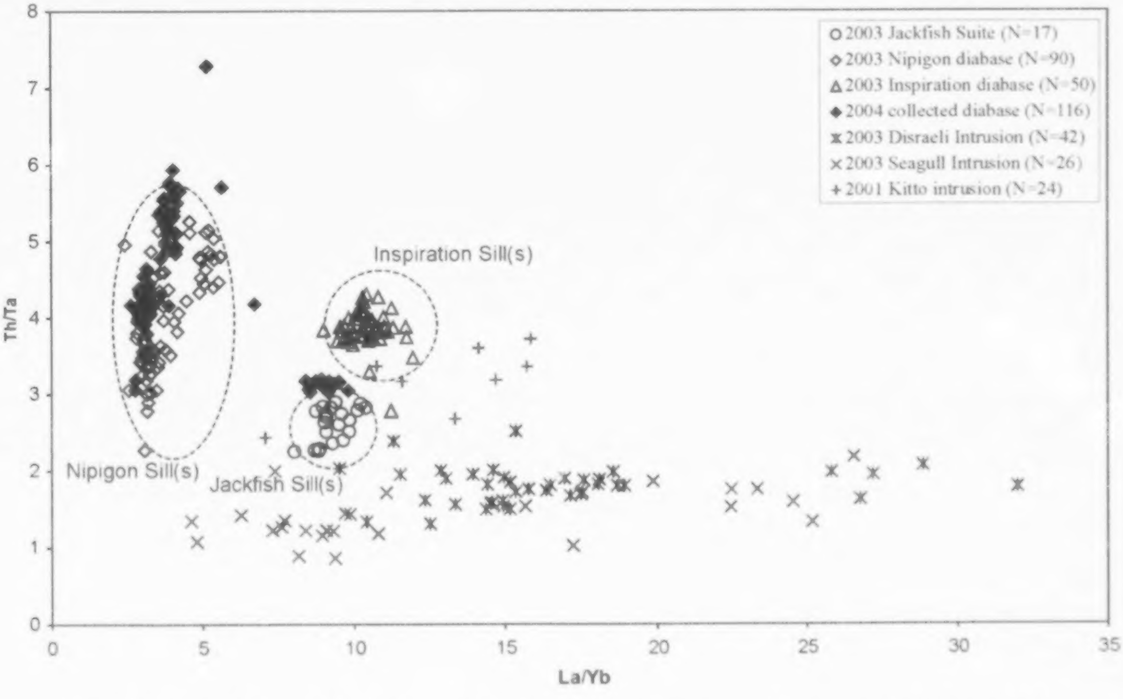

Figure 49.4. Th/Ta versus La/Yb for samples from the Nipigon Embayment. Data sources as for Figure 49.3.

Table 49.1. Average whole-rock, major element analyses for each of the main Proterozoic sill types within the western Nipigon Embayment. Data are *from* Macdonald and Tremblay (2004a) and unpublished, preliminary data from the 2004 field season. All elements reported were analyzed by X-ray fluorescence (XRF) on fused and pressed powder pellets, at the Geoscience Laboratories, Ontario Geological Survey, Sudbury.

Element (wt %)	Nipigon diabase sill n=182	Inspiration diabase sill n=50	Jackfish suite rocks (2003) n=19	Possible Jackfish suite n=18
SiO_2	49.07	52.03	44.67	48.83
TiO_2	1.53	1.24	1.98	2.82
Al_2O_3	14.50	15.17	8.62	14.03
Fe_2O_3	15.42	11.92	17.42	15.53
MnO	0.22	0.18	0.21	0.18
MgO	5.99	5.70	16.82	5.21
CaO	10.05	9.59	7.47	9.03
Na_2O	2.63	2.91	1.96	3.21
K_2O	0.54	1.18	0.54	0.76
P_2O_5	0.17	0.16	0.18	0.24
LOI	0.30	0.65	0.45	0.68
Total	100.35	100.72	100.15	100.51

Alteration

Most alteration observed was related to the development of hornfels in the Sibley Group sedimentary rocks adjacent Nipigon diabase sill contacts. Typical alteration in the sedimentary rocks related to contact metamorphism includes pink potassium feldspar veins, weak to moderate chloritization, and weak to moderate development of actinolite both within the rock and along fracture surfaces.

Nipigon diabase sills typically develop medium- to coarse-grained leucocratic diabase pods, veins, aplite veins, and potassium feldspar-rich pods or monzogranitic varieties of diabase, proximal to Sibley Group contacts (Photos 49.2b and 49.2f). The development of potassium feldspar-rich pods and monzogranite has been suggested to result from the assimilation of Sibley Group sedimentary rock (Hart and Magyarosi 2004a).

Deposition of alteration minerals along joint surfaces in Nipigon diabase sill is common and may be due to late magmatic hydrothermal fluids circulating through these joints in the final stages of cooling or due to percolation of later groundwater fluids. These joints may commonly contain chlorite, actinolite, magnetite, and possibly tremolite or wollastonite (Photo 49.2c).

Hematite alteration is also common within Nipigon diabase sills where diabase with a higher magnetite content has been weathered.

Specular and earthy varieties of hematite were observed to occur in a red to maroon mudstone of the Sibley Group in the Circle Lake area. Specular hematite in these outcrops is typically fracture controlled.

Structure

Fabric development in the Archean rocks generally consists of weak to moderate intensity, east- to northeast-trending mineral foliations that correlate well with regional trends in the central Wabigoon Subprovince.

There are at least 3 prominent fault sets within the map area:

1. a northeast-trending set
2. a north-trending set
3. a northwest-trending set

The northeast-trending set, such as in the Max–Mawn lakes area, appears to correlate with structures in the central Wabigoon Subprovince such as the southern margin of the Lac des Iles belt (Max Creek fault) and the Max Lake fault (*see* Figure 49.2). The geophysical signature of many of these structures disappears or become obscured to the east by the strong magnetic signature of the overlying Nipigon diabase sills (Ontario Geological Survey 2004).

A set of subparallel north-trending faults, which include the Black Sturgeon fault, may represent the failed arm of the Keweenawan Midcontinent Rift (Sutcliffe 1991). Near Black Sturgeon Lake, and further north toward Chief Bay, a prominent set of northwest-trending faults is also present. Coates (1972) suggested that these northwest-trending faults in the Black Sturgeon Lake area are *en échelon* and that they controlled the collapse of a large segment of the underlying basement rocks, thereby preserving the Sibley Group sedimentary rocks west of the Black Sturgeon fault. Furthermore, Coates (1972) suggested that displacement of these "blocks" was hinge-like, with little movement in the northwest and greater offset to the southeast. The intersection of these north-trending and northwest-trending faults may form several northwest-elongated blocks (*see* Figure 49.2) with greatest subsidence or offset at the southeast intersection point. Vertical offset along the northwest-trending faults is indeterminate, however, significant lateral offset along the northwest- and north-trending structures seems unlikely as Hart and Magyarosi (2004a) observed little lateral displacement across the Black Sturgeon fault, based on correlation of the Archean iron formation on either side of Black Sturgeon Lake.

A schematic preliminary cross section was constructed to illustrate the subsurface geology of the map area, as well as some of the offset along the north-trending faults. The cross section (A–A′, Figure 49.5) is approximately 35 km long and extends from east of Geikie Lake to the east shore of Black Sturgeon Lake. A significant amount of vertical offset along the Black Sturgeon fault must be present, however, the exact amount of offset is indeterminate, as there are no marker horizons and only Archean basement is present on the east side of the Black Sturgeon fault along the trace of the cross section. In the Circle Lake area, if Sibley outcrops mapped in the Poshkokagan River valley are part of the same sequence as similar units noted in a drill hole near the centre of Black Sturgeon Lake, then there is at least 75 m of vertical offset on the north-trending Circle Lake fault (*see* Figure 49.5). Offset along another north- to northeast-trending fault is apparent if the elevation of similar Sibley Group rock units is compared in outcrop east of Highway 527 and in drill hole east of Geikie Lake. This correlation suggests at least 250 m of offset along this fault (*see* Figure 49.5).

Cross section A–A′ (*see* Figure 49.5) suggests the presence of 2 separate diabase sills. Drill hole A-2 (Hudson Bay Exploration and Development Company Limited 1982), located near the centre of Black Sturgeon Lake, west of the Black Sturgeon fault, indicates the presence of diabase beneath a 48 to 55 m thick unit of Sibley Group sedimentary rocks (Table 49.2). Drilling by Platinum Group Metals Limited (2003) on the Pebble property, approximately 13 km east of Poshkokagan Lake, also indicated the presence of a second sill at depth (Platinum Group Metals Limited 2003). Diamond-drill holes PB-02-01 and PB-02-02 (not present on the cross section) each indicate 45 to 54 m, respectively, of Sibley Group sedimentary rocks separating an upper and lower diabase sill (*see* Table 49.2) (Platinum Group Metals Limited 2003). A similar thickness of Sibley Group sedimentary rocks, and the possible presence of an upper and lower diabase sill, were also noted in drill holes in the Mikinak Lake (MW02-01) and Grand Bay areas (GB-01-01) (*see* Table 49.2). Drill hole MW02-01, located approximately 0.5 km north of Mikinak Lake, contains an upper and lower diabase sill separated by a thickness of 45 to 50 m of Sibley

Table 49.2. Summary of drill core logs from the west-central Nipigon Embayment that intersect more than one diabase sill. Interval thickness (shown in brackets) is not dip corrected. All data are in metres.

Drill Hole Number	Company and Reference	Elevation	Overburden	Upper Sill	Sibley Group	Lower Sill
A-2	Hudson Bay Exploration and Development Co. Ltd. (1982)	257	0–56.0 (56)	Not observed	56.0–111.4 (55.4)	111.4–142.5 (31.1)
98-60	North American Palladium (1998)	307	0–7.4 (7.4)	7.4–22.6 (15.2)	22.6–39.9 (17.3)	39.9–304.8 (264.9)
PB-02-01	Platinum Group Metals Ltd. (2003)	408	0–9.0 (9)	9.0–37.7 (28.7)	37.7–82.2 (44.5)	82.2–180.0 (97.8)
PB-02-02	Platinum Group Metals Ltd. (2003)	425	0–3.0 (3)	3.0–46.4 (43.4)	46.4–100.0 (53.6)	100.0–150.0 (50)
MW-02-01	Teck Cominco Limited (2003)	262	0–31.7 (31.7)	31.7–96.5 (64.8)	96.5–145.0 (48.5)	145.0–353.0 (208)
GB-01-01	Canplats Resources Corp. (2001)	270	0–9.0 (9)	9.0–127.9 (118.9)	127.9–209.4 (81.5)	209.4–410.0 (200.6)

Group sedimentary rocks that are interspersed with three, 20 cm to 3.5 m, intervals of chilled diabase (Teck Cominco Limited 2003). The upper and lower diabase sills in drill hole GB-01-01 are separated by a thickness of 76.5 m of Sibley Group sedimentary rocks (Canplats Resources Corporation 2001). The presence of a second diabase sill at depth is also supported by field observations made in 2004 north-northeast of Black Sturgeon Lake and in the Poshkokagan River valley. In these areas, several Nipigon diabase outcrops at different elevations are separated by 1 to 5 m of Sibley Group sedimentary rocks. Although this could represent Sibley Group "rafts" within the diabase, the thickness of the sedimentary rocks in the Pebble, Black Sturgeon, Grand Bay and Mikinak drill holes would preclude this interpretation.

RECOMMENDATIONS FOR EXPLORATION

Archean metawacke outcrops along the Mawn Lake road locally have been prospected for gold and base metals, particularly in rusty outcrops. If the comparison between the Max–Mawn lakes area and the southern contact of the Beardmore–Geraldton greenstone belt is valid, than the Max Creek deformation zone warrants exploration for gold mineralization, similar to that found along the Paint Lake deformation zone in the Beardmore–Geraldton area. Drilling in one of the Max Lake panels north of Geddes Lake by Canamax Resources Incorporated (1984) intersected 5.45 ppm Au over a 3 foot interval in iron formation.

All geochemical samples collected, as a part of this study will be analyzed for gold, platinum and palladium. Results will be published in 2005. No rusty zones or other obvious mineralized areas were identified during the 2004 mapping program.

Platinum group element mineralization in mafic rocks of the Nipigon Embayment is typically hosted within the mafic to ultramafic suite rocks, such as the Seagull and the Disraeli intrusions. Although these types of intrusions are not exposed at surface in the map area, several authors (e.g., Middleton 2001) have suggested that their distribution is related to the north-trending Black Sturgeon fault. If true, then the parts of the map area adjacent to many of the north- and northwest-trending structures in the map area that are interpreted to be extensions of, or splays of the Black Sturgeon fault may be good areas to explore for subsurface Cu-Ni-PGE mineral deposits.

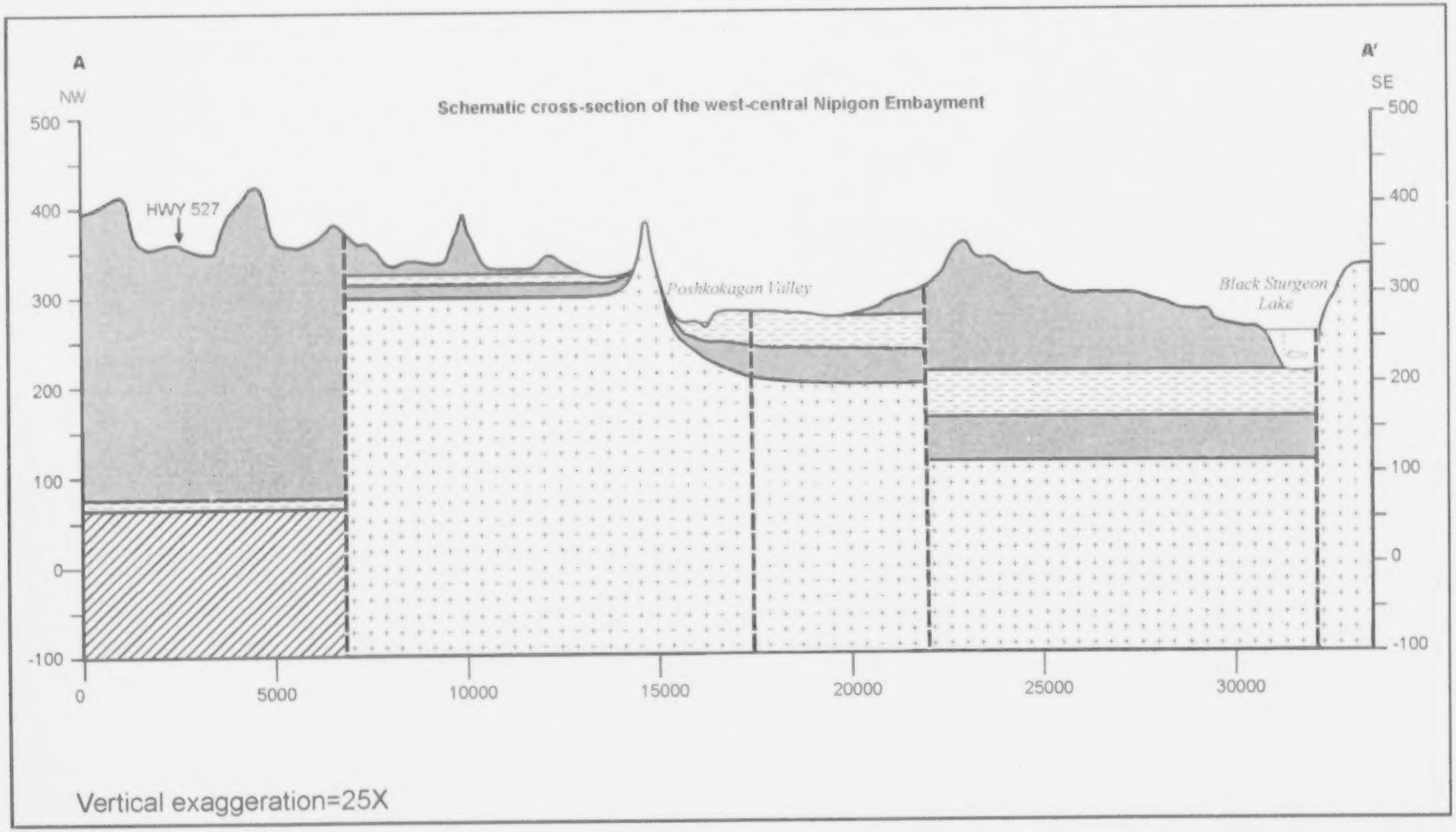
Schematic cross-section of the west-central Nipigon Embayment
A
NW
A′
SE
HWY 527
Poshkokagan Valley
Black Sturgeon Lake
500
400
300
200
100
0
-100
0
5000
10000
15000
20000
25000
30000
Vertical exaggeration=25X

Figure 49.5. Geological cross section from north of Cheeseman Lake to Black Sturgeon Lake. Location of cross section is shown in Figure 49.2 by line A–A′. Symbology same as that used in Figure 49.2. Vertical exaggeration is 25×.

REFERENCES

Canamax Resources Incorporated 1984. Report of diamond drilling in the Max Lake area; Thunder Bay Resident Geologist's office, assessment file, ERMES #52H03NW007 and associated files.

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50. Lake Nipigon Region Geoscience Initiative. Stratigraphy of the Sibley Group and its Relationship to Sedimentary Units of the Basal Osler Group and the Nipigon Sills

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INTRODUCTION

Studies of the Sibley Group, and its stratigraphic relationships with the Nipigon sills, have been undertaken as a contribution to the Lake Nipigon Region Geoscience Initiative (Rayner, this volume). In the previous year, advances were made in understanding the three-dimensional organization of the Nipigon Embayment and some preliminary results have been summarized (e.g., Magyarosi et al. 2004). During the summer of 2004, work focussed on 3 areas. One endeavour concerned deciphering Sibley Group stratigraphy in the regions of Nipigon Bay and the Rossport area where complete sections of the Sibley Group are well preserved and exposed. This included investigations of the basal sedimentary units of the Osler Group and their stratigraphic relationships with Sibley Group rocks. A second focus involved investigating Sibley Group exposures in the southern portion of Lake Nipigon and their stratigraphic relationship to diabase sills in that area. This consisted of visiting outcrop exposures in the area as a continuation of previous diamond-drill core and outcrop logging conducted in 2003. A final endeavour was to develop a detailed understanding of the paleoenvironments represented by the Pass Lake and Rossport Formations of the Sibley Group with a particular focus on determining the seawater versus continental influences on various well-preserved chemical sediment types. Work in this area has involved detailed logging of both diamond-drill core and outcrop combined with geochemical sampling of the lower portions of the Sibley Group (Pass Lake and Rossport formations). It is hoped that this line of investigation may reveal consistent stable isotopic signatures in portions of the Sibley Group to aid in chronostratigraphic correlations across the basin.

The focus of this article is the new stratigraphic data and how these relate to the overall geology of the Nipigon Embayment. With this and previously collected data, a working model for the development of the Sibley Basin and its later relationship with the Nipigon Sills can be developed. In general, correlation of individual sill complexes is difficult because of the homogeneous lithological character of the sills. The lithostratigraphic subdivisions of the Sibley Group, which in addition to older Precambrian rocks, host the Nipigon sill complexes, provide a method by which individual sill complexes may be distinguished and correlated. Further, the distribution of stratigraphic units in the Sibley and basal Osler Group in relation to fault systems within the region can be used to decipher phases in the Mesoproterozoic subsidence history of the area.

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.50-1 to 50-5.

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SIBLEY GROUP LITHOSTRATIGRAPHY

The Sibley Group has previously been subdivided into 3 formations: from bottom to top, these are the Pass Lake, Rossport and Kama Hill formations. Member subdivisions and lithological characteristics of these are described in Franklin et al. (1980), Cheadle (1986) and Rogala (2003). Here, the focus is new data on the upper Sibley Group and the reader is referred to the above work for descriptions of the lithologies in the lower Sibley Group. Two upper Sibley Group formations, the Outan Island and Nipigon Bay formations, are described by Rogala (2003) and represent approximately 500 m of stratigraphy, exposed primarily in diamond-drill cores from Nipigon Bay.

The Outan Island Formation consists of mudstone, laminated siltstone and/or mudstone, siltstone, sandstone and intraformational conglomerate lithofacies. Two members of the Outan Island Formation have been described by Rogala (2003). The lower Lyon Member is dominated by fine-grained lithofacies while the upper Hele Member contains thicker more coarsely grained sandstones with thin intraformational conglomerate interbedded with red siltstones. Further work has found that portions of the Outan Island Formation contain extensive intraformational conglomerates. These conglomerates consist of poorly sorted blocks of material up to 1 to 2 m in diameter which containing centimetre-scale laminae of current-rippled fine-grained sandstones and red siltstones, symmetrically rippled fine-grained sandstones and red siltstones, possibly hummocky cross-stratified fine-grained sandstones and horizontally laminated red siltstones and shales, set in a poorly sorted matrix of sandstone (Photo 50.1a). Many of these blocks contain material with similar lithologies to the Kama Hill Formation. Undisturbed beds with similar sedimentary characteristics are also present at numerous localities (e.g., Photo 50.1b). South of the town of Red Rock on the Lake Superior shoreline, exposure of this intraformational conglomerate is continuous for several kilometres. Smaller scale intraformational conglomerates containing similar lithologies are found on the Trans-Canada Highway west of Dorion and in the map area of Hart and Whaley (this volume).

A second formation in the upper Sibley Group (Rogala 2003) is termed the Nipigon Bay Formation. The Nipigon Bay Formation consists of primarily large-scale sets of planar cross-stratified medium-grained sandstones (Photo 50.1c). These are exposed on Simpson and St. Ignace islands on Lake Superior and in some diamond-drill core from Nipigon Bay. The Nipigon Bay Formation is unconformably overlain by basal sedimentary units of the Osler Group and this contact is exposed on the north shores of Simpson and St. Ignace islands on Lake Superior. Paleocurrents for the Nipigon Bay Formation show a southwest trend (Figure 50.1).

DEPOSITIONAL ENVIRONMENTS OF THE UPPER SIBLEY GROUP

The Kama Hill Formation has been interpreted as a shallow mud flat environment, based on the presence of halite casts and mud cracks (Franklin et al. 1980; Cheadle 1986; Rogala 2003). This interpretation fits well in a logical evolution from the underlying paleoenvironments of the Rossport Formation described by Cheadle (1986). The interpretation is problematic, however, when the overlying Outan Island Formation is taken into consideration. The Outan Island Formation is interpreted to represent a coarsening upwards deltaic succession overlain by fluvial deposits (Rogala 2003). From this standpoint, the Kama Hill Formation may represent the lowest units in this general coarsening upwards trend. Halite casts have not been encountered in the Kama Hill Formation during the coarse of this study. Furthermore, green shales in the lowest portions of the Kama Hill Formation on Channel Island, plus the presence of well-laminated, rippled, wave-rippled and possibly hummocky cross-stratified fine-grained sandstones and shales attest to a largely subaqueous environment rather than subaerial mud flats. Mud cracks are found to be less common than reported by previous authors (e.g., Franklin et al. 1980; Cheadle 1986) and, where present, may also be interpreted as syneresis cracks. Extensive intraformational

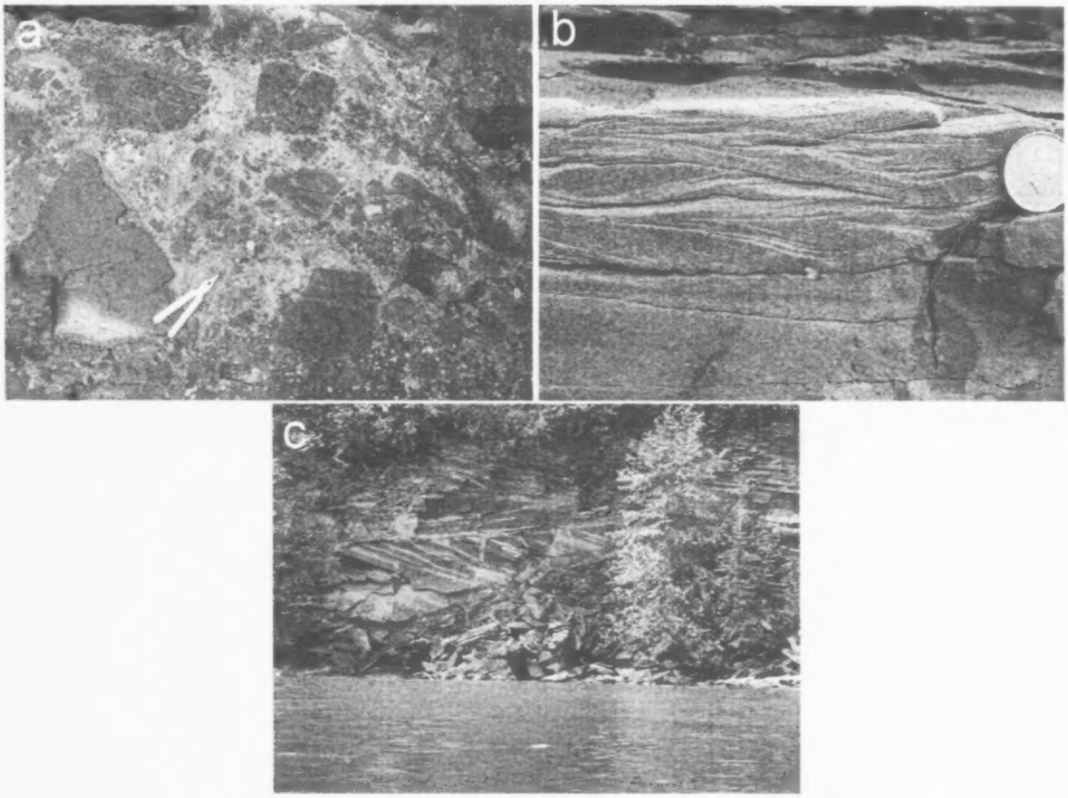

Photo 50.1. a) Intraformational conglomerate (Outan Island Formation) south of Red Rock, Lake Superior. b) Wave-rippled fine-grained sandstone, Outan Island Formation, south of Red Rock, Lake Superior. c) Nipigon Bay Formation cross-stratified eolian sandstones, Simpson Island, Lake Superior.

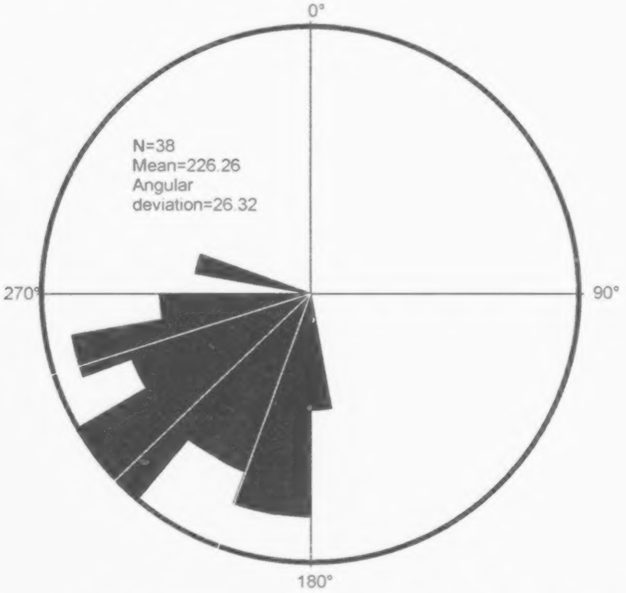

Figure 50.1. Paleocurrent rose for the Nipigon Bay Formation, St. Ignace and Simpson islands, Lake Superior.

conglomerates may represent large-scale slump features forming on delta slopes. The interpretation of the depositional environment of the Nipigon Bay Formation is fairly straightforward. Homogeneous metre-scale sets of planar cross-stratified medium-grained sandstones indicate that the Nipigon Bay Formation is of eolian origin (Rogala 2003).

STRATIGRAPHIC RELATIONSHIPS BETWEEN THE SIBLEY GROUP, OSLER GROUP AND NIPIGON SILLS

The Sibley Group is well exposed in the regions adjacent to Lake Superior (Red Rock, Kama Hills, Nipigon Bay and Rossport) and is, for the most part, unmetamorphosed. A relatively thick sill caps the Sibley Group over portions of this area, although it would appear that a second sill complex, as is found to the north, may be absent. Exposures on the mainland near the Trans-Canada Highway show the sill intrudes either the Kama Hill Formation or, in places, the Fire Hill Member of the upper Rossport Formation. Diamond-drill core from Nipigon Bay (e.g., NB-97-2) intersects all stratigraphic units of the Sibley Group, with only minor diabase intrusions of metre-scale thickness. Below the Sibley Group strata, a 60 m thick fine-grained mafic intrusive rock cuts Archean basement rocks near the base of this drill hole, approximately 1 km below the level of Lake Superior. The relationship between this sill and the Nipigon sills or Osler Group is not known.

The contact between the lower sedimentary units of the Osler Group and the Sibley Group is exposed at various locations near Rossport and in the large islands of Nipigon Bay. The Nipigon Bay Formation is restricted in distribution to the northern sections of St. Ignace and Simpson islands. At these locations, the Sibley Group–Osler Group contact occurs at the top of the Nipigon Bay Formation. Farther to the east, the contact is again exposed on Copper Island, east of the town of Rossport. At this location, the Osler Group is in contact with a portion of the Rossport Formation. The preservation of the Nipigon Bay Formation appears to be the result of it being faulted downward some time prior to the deposition of the first units assigned to the Osler Group.

Farther north, in the region between the southern shore of Lake Nipigon and the Trans-Canada Highway, Sibley Group exposures are common. This area is represented by the areas mapped by Hart and Magyarosi (2004) and Hart and Whaley (this volume). Preliminary cross-sections from this area show that two major sills intrude Sibley Group strata (Magyarosi et al. 2004). Sibley Group rocks exposed in this region include the majority of the stratigraphic units from the base extending upward to the Kama Hill Formation and, in places, units of the lower Outan Island Formation.

A wealth of diamond-drill core exists for the large area immediately to the west of Lake Nipigon. In this region, the severity of contact metamorphic effects induced by sill intrusions increases significantly. This makes the identification of Sibley Group stratigraphic units much more difficult. A relatively simple stratigraphy is present in most diamond-drill holes and consists of

- a thick upper diabase complex
- an upper, variable thickness of hornfelsed Sibley Group material
- a thick lower diabase complex, and
- a lower section of Sibley Group material or Archean basement

Thin, metre-scale intrusions cutting the Sibley Group are also common. To the east, across the Black Sturgeon fault, the Sibley Group thins and becomes locally absent. In the vicinity of the along-strike projection of the Black Sturgeon fault near Tchiatang Bluff, Sibley Group rocks dip quite steeply, suggesting that motions along the fault occurred after Sibley Group deposition. To the east, diamond-drill core control is lacking, however, outcrops of Sibley Group rocks, probably correlative with the Rossport Formation form thin (maximum exposure thickness about 15 m) units overlain and underlain by sills. Along the west shore of Pipestone Bay, the Sibley Group crops out as a series of outcrops consisting of thinly bedded contact-metamorphosed pale green, medium-grained, sandstones interbedded with darker green calcareous siltstones. These may be correlative with Sibley Group–Nipigon Sill contacts noted in diamond-drill cores to the west. The nature of sill contacts is often not completely concordant and the observed dip of sills (from chilled sill tops and Sibley Group–Nipigon Sill contacts) is quite varied and commonly difficult to accurately determine.

GEOCHEMISTRY OF THE SIBLEY GROUP

The Sibley Group preserves a variety of genetically distinct chemical sediments. These include a variety of sedimentologically and petrographically distinct carbonate- and sulphate-bearing rocks. Stromatolitic carbonates, pedogenic carbonates from interpreted calcretes, and micritic carbonates have been sampled for trace element, strontium and stable isotope analyses from both outcrops and diamond-drill core. Sulphates from diamond-drill core have been sampled in the form of fine-grained nodules in micritic carbonates from the Channel Island Member of the Rossport Formation and as coarser nodules in overlying red siltstones of the Fire Hill Member. Stratigraphic geochemical variations and variations between distinct chemical sediment phases will provide information on the marine versus continental nature of the Sibley Group and also information about the paleohydrology of the Sibley Basin. Interpretation of geochemical data collected thus far is preliminary and trace element and some isotopic analyses are pending.

CONTINUING WORK

Data from field work, and OGS mapping projects conducted under the Lake Nipigon Region Geoscience Initiative, are providing interesting new information regarding the evolution of the Sibley Group, the stratigraphy of the Nipigon Sills and the history of the Midcontinent Rift. Work is in progress to compile a series of geological cross-sections to illustrate the three-dimensional geometry of the Nipigon Embayment and the lithostratigraphy of the Sibley Group.

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51. Lake Nipigon Region Geoscience Initiative. Geochemistry and Mineralogy of the Nipigon Diabase Sills

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INTRODUCTION

This study is being undertaken as part of the Lake Nipigon Region Geoscience Initiative (LNRGI), which is a project funded by both the public and private sector to attract mineral exploration to the Lake Nipigon region (Rayner, this volume). The focus of this component of the LNRGI is to evaluate the geochemical and mineralogical composition of the Nipigon sills and investigate the nature of sill emplacement. The Nipigon sills have been interpreted to be an intrusive basaltic sequence emplaced into the flat-lying, relatively undeformed, Mesoproterozoic Sibley Group sediments during the 1.1 Ga Keweenawan rift event centred in the Lake Superior region (Sutcliffe 1987). The sills cover an area of approximately 11 000 km^2, representing a minimum erupted volume of 10 000 km^3 (Sutcliffe 1987). Basement rocks in the Lake Nipigon region are primarily Archean, with northern areas underlain by metavolcanic rocks of the Wabigoon Subprovince, whereas the southern and central areas are underlain by metavolcanic and metaplutonic rocks of the Wabigoon Subprovince, and metasedimentary rocks of the Quetico Subprovince (Figure 51.1).

This second year of a two-year program, focussed on additional sample collection from Lake Nipigon and acquisition of laboratory data. During the 2004 field season, 79 outcrop samples from the northern and eastern shores of Lake Nipigon were collected (*see* Figure 51.1). Geochemical analyses of these samples, and those from the 2003 field season, were obtained from the University of Saskatchewan and the Ontario Geological Survey analytical facilities. A preliminary U/Pb age of 1110±2.6 Ma was obtained from baddeleyite from a diabase sill near Havoc Lake (L.M. Heaman, University of Alberta, personal communication, 2004). A possibly slightly older, preliminary baddeleyite age of 1113±2.4 Ma was obtained from a diabase sill in the Muskrat Lake area (L.M. Heaman, University of Alberta, personal communication, 2004). These new U/Pb ages are within error of the baddeleyite and zircon age of $1109\ ^{+4}/_{-2}$ Ma from 2 diabase sills that was reported by Davis and Sutcliffe (1985).

RESULTS

Preliminary petrographic observations for the Nipigon sills suggests that they are petrographically uniform and are typically ophitic to subophitic gabbronorite (IUGS classification) with plagioclase compositions between An$_{30}$ (andesine) and An$_{50}$ (labradorite). Pyroxene chadacrysts generally measure up to 5 mm, with plagioclase oikocrysts up to 1 mm commonly occurring as randomly oriented laths, but occasionally as glomeroporphyritic plagioclase. Pyroxene occurs as both orthopyroxene and clinopyroxene, in approximately 40 and 60 modal percent abundance, respectively. Olivine is observed as a trace mineral in both diamond-drill core samples from Shillabeer Lake and from sills exposed on the

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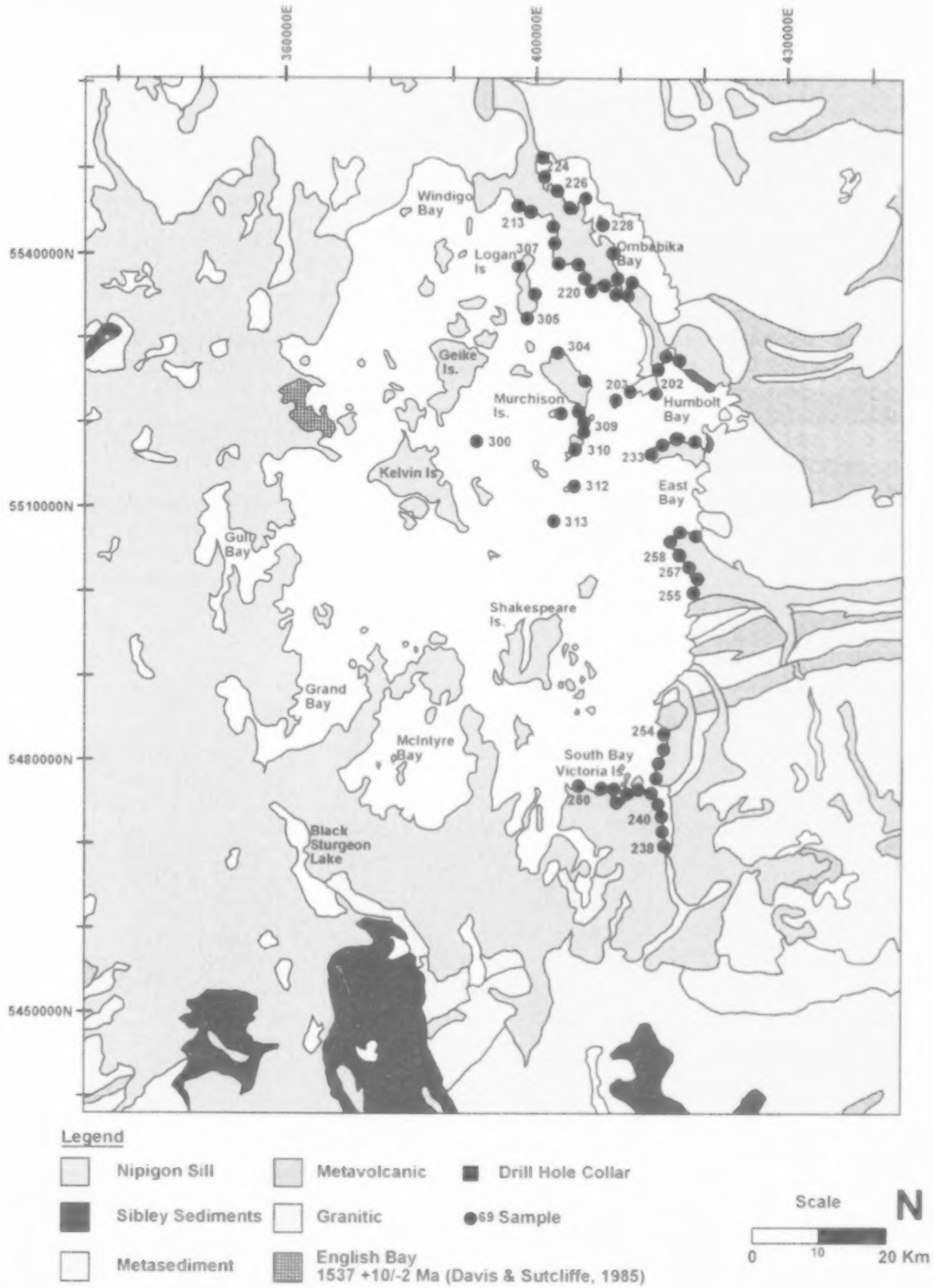
360000E
400000E
430000E
5540000N
5510000N
5480000N
5450000N
Windigo Bay
Logan Is
Geike Is.
Murchison Is.
Kelvin Is
Gull Bay
Grand Bay
McIntyre Bay
Black Sturgeon Lake
Shakespeare Is.
Ombabika Bay
Humbolt Bay
East Bay
South Bay
Victoria Is.
224
226
213
228
307
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304
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313
258
257
255
254
260
240
238
Legend
Nipigon Sill
Sibley Sediments
Metasediment
Metavolcanic
Granitic
English Bay
1537 +10/-2 Ma (Davis & Sutcliffe, 1985)
Drill Hole Collar
69 Sample
Scale
N
0
10
20 Km

Figure 51.1. Regional geology map of the Lake Nipigon area showing the locations of samples collected in 2004 (*modified after* Sutcliffe 1986).

shore of northwest Lake Nipigon. Olivine tends to occur as subhedral to anhedral grains in trace amounts up to 5 modal percent, with little to no observable alteration. Olivine compositions range from Fo_{48} to Fo_{63}.

Preliminary geochemical results suggest that the sills in the southern portion of the study area can be subdivided into 3 geochemically distinct suites (Figures 51.2 and 51.3). The Main Nipigon suite comprises the majority of samples collected from both outcrop and diamond-drill core. The suite is characterized by magnesium numbers ranging from 30 to 65, Zr/Y ratios of 3 to 4.5, and slight light rare earth element (LREE) enrichment (La/Sm_{cn} = 1.3 to 1.9). This suite is also characterized by a strong negative Nb anomaly (Nb/Nb* = 0.43 to 0.60), and weak negative Ti and Y anomalies.

The Shillabeer suite is defined by 6 samples collected from diamond-drill holes DDH3 and DDH5 recovered from the Shillabeer Lake area (Richardson, Hollings and Heggie 2003). The Shillabeer suite is characterized by magnesium numbers ranging from 45 to 75, Zr/Y ratios ranging from 7.5 to 10, and a strong LREE enrichment (La/Sm_{cn} = 2.1 to 2.8). This suite also shares the pronounced negative Nb anomaly and weak Ti and Y anomaly of the Main Nipigon suite, but is distinguished from the Main Nipigon suite by moderately negative Zr and Hf anomalies (*see* Figure 51.2).

The McIntyre suite is represented by 2 samples (LN 45 and LN 101) from the north end of McIntyre Bay in southern Lake Nipigon (Richardson, Hollings and Heggie 2003). This suite is characterized by magnesium numbers ranging from 40 to 45, a Zr/Y approximately 7 and moderate LREE enrichment indicated by La/Sm_{cn} ratios of 1.8 to 2.0. The McIntyre suite shares the negative Nb and Y anomalies of the other 2 suites, but lacks the negative Ti, Zr and Hf anomalies (*see* Figure 51.2).

DISCUSSION

The available geochemical data for the whole Lake Nipigon region suggests the possibility of at least 5 geochemically distinct sills in the Nipigon Embayment. MacDonald and Tremblay (2004) reported that the Inspiration and Jackfish sills, located near Inspiration Lake and Jackfish Island, respectively, were geochemically distinct from the 3 sill suites identified in the southern portion of the basin (*see* Figures 51.2 and 51.3). The Inspiration sills have higher LREE abundances than the Main Nipigon suite sills, but also has moderately negative Nb and Ti anomalies (*see* Figure 51.2). The Jackfish sill is less enriched in LREE than the Inspiration sills, and is only slightly more enriched in LREE than the Main Nipigon suite (*see* Figure 51.2). Diabase samples collected from the west shore of Lake Nipigon as part of this study are from the Main Nipigon suite, not the Inspiration sills. This may reflect the fact that the lakeshore samples are from a lower topographic elevation and therefore represent a separate intrusion or intrusions that underlie the Inspiration sills. Chill margins observed between diabase units in the northern part of Chief Bay, and the eastern shoreline of South Bay in southwestern Lake Nipigon, as well as observations reported by Hart and Whaley (this volume), suggest that there may be significant time gaps between emplacement of individual sills, thereby allowing for the evolution of distinct magmatic sources. The overlap between the McIntyre, Jackfish and Inspiration suites shown in Figure 51.3 is the subject of further study, but could be related to magma mixing or contamination.

Preliminary ε_{Nd} isotope data range from 0 to −2 for the Main Nipigon suite, approximately −3 for the McIntyre suite, and approximately −5 for the Shillabeer suite, and may be an additional tool to further define these units. The ε_{Nd} data suggest that contamination of the sill suites by older continental crust (either Archean basement or Sibley Group sediments) may be responsible for the differences in trace element geochemistry. This topic is being studied further as part of the senior author's Masters thesis at Lakehead University.

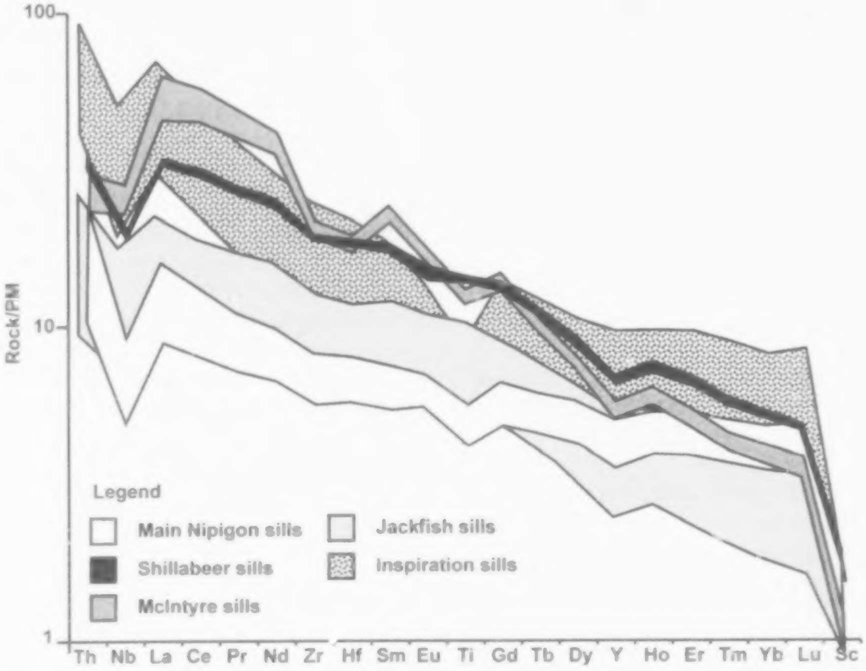

Figure 51.2. Primitive mantle (PM) normalized diagrams for the 5 suites of diabase sills (normalizing values of Sun and McDonough 1989).

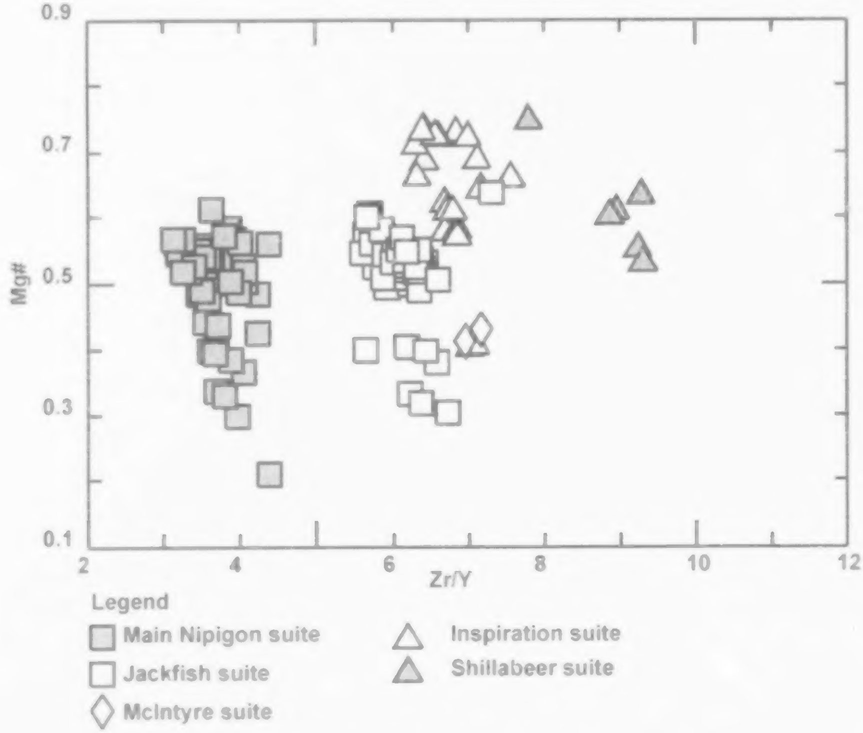

Figure 51.3. Plot of Mg# versus Zr/Y for the 5 suites of diabase sills.

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52. Project Unit 03-023. Lake Nipigon Region Geoscience Initiative. Surficial Geochemistry and Mapping Case Studies Project: Update and Preliminary Results

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[1]Sedimentary Geoscience Section, Ontario Geological Survey, Sudbury, Ontario

INTRODUCTION

The surficial geochemistry and mapping case studies project is part of the Lake Nipigon Region Geoscience Initiative (LNRGI) administered by the Ontario Prospectors Association (OPA). The goal of the LNRGI is to stimulate mineral exploration for platinum group element (PGE) deposits, specifically within the Nipigon Embayment. This goal is to be realized by sponsoring geoscience studies in new and proven technologies and methods. The surficial geochemistry and mapping project focusses on the acquisition, interpretation and dissemination of multi-media geochemical data and surficial map products. The case study areas selected by the LNRGI scientific committee are located around known PGE mineralization and PGE anomalous lake sediment sites (Figure 52.1). The Lac des Iles and Tib Lake study areas cover known PGE mineralization in bedrock, while the Cheeseman Lake, Right Angle–Muskrat–Circle lakes and Tarrison Lake study areas cover significant PGE lake sediment anomalies.

The majority of field work for this project was completed during the 2003 field season. During the 2004 field season, additional sampling and check sampling of various surficial media was completed over a period of approximately 5 weeks between June 14 and August 25. Access to the case study areas was accomplished by a combination of 4×4 truck, all-terrain vehicles (ATVs), boat and on foot.

GEOLOGY

Bedrock mapping of the Nipigon Embayment (west and southwest of Lake Nipigon) is being completed by the Ontario Geological Survey under the auspices of LNRGI. Reports and maps (1:50 000 scale) for the areas north and south of the surficial case study areas have been recently published (MacDonald 2004; Hart and Magyarosi 2004). Bedrock mapping encompassing the 5 surficial case study areas was completed by the OGS during the summer of 2004 (MacDonald, Tremblay and Easton, this volume).

The OGS also initiated a detailed Quaternary mapping program of the Lake Nipigon study area in 2004 (*see* Barnett, this volume). Prior to this, the Quaternary geology of the area south and west of Lake Nipigon had been investigated at only a regional scale. A synopsis of previous Quaternary geology investigations in the Nipigon plate area is contained in Dyer and Barnett (2003).

Summary of Field Work and Other Activities 2004,
Ontario Geological Survey, Open File Report 6145, p.52-1 to 52-6.

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SAMPLING AND LABORATORY METHODS

Well-established methods and protocols for all surficial media sampling were employed during this project. Details regarding specific sampling methods for each type of surficial media have been previously documented (Dyer and Barnett 2003).

Precise global positioning system (GPS) co-ordinates were collected at all sample sites utilizing Trimble GeoXM™ and/or GeoExplorer® 3 receivers. All GPS co-ordinates were collected and saved in North American Datum 1983 (NAD 83), Zone 16. Daily downloading to a laptop computer and periodic backup of data, by recording to CD-ROM, ensured data safety and integrity. Sample site locations were also plotted on airphotos and/or 1:50 000 scale topographic maps in the field at the time of collection. Field duplicates for all sample media were collected at a rate of approximately 1 sample in 20.

All surficial media samples were dried before being shipped to an external laboratory for preparation and analysis. Analysis of inorganic and organic media included aqua regia digestion followed by inductively coupled plasma mass spectrometry–optical emission spectroscopy (ICP–MS–OES) for most major, minor and trace elements, and fire assay–inductively coupled plasma mass spectrometry (FA–ICP–MS) for gold and PGEs. Waters were analyzed by ICP–MS–OES for a suite of over 50 elements. For reliable gold and PGE data, and in order to achieve the required detection limits of this project, waters underwent a proprietary treatment to recover gold, palladium and platinum that may have adhered to the walls of the sample bottles. This was followed by direct high-resolution (HR)–ICP–MS analysis.

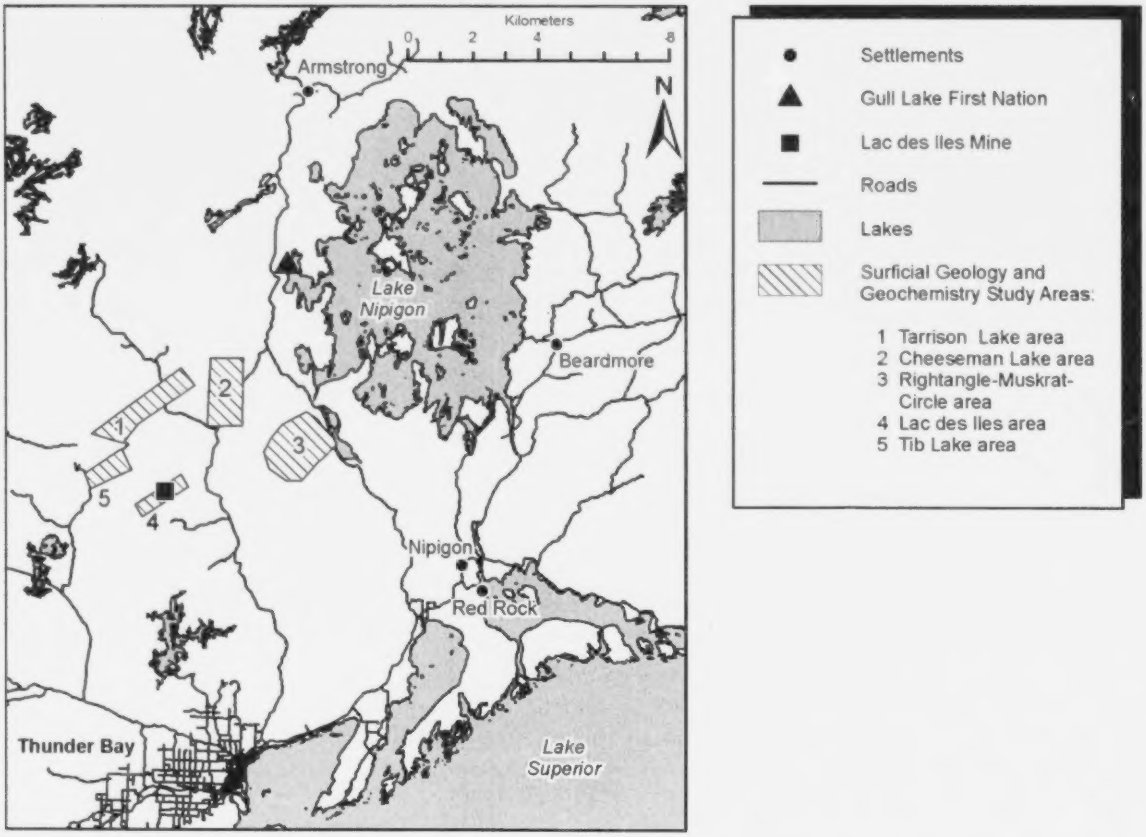
Kilometers
0
2
4
8
N
Armstrong
Lake Nipigon
Beardmore
Nipigon
Red Rock
Thunder Bay
Lake Superior
1
2
3
4
5
● Settlements
▲ Gull Lake First Nation
■ Lac des Iles Mine
Roads
Lakes
Surficial Geology and Geochemistry Study Areas:
1 Tarrison Lake area
2 Cheeseman Lake area
3 Rightangle-Muskrat-Circle area
4 Lac des Iles area
5 Tib Lake area

Figure 52.1. Location of case study areas, LNRGI surficial geochemistry and mapping project.

Rock samples underwent a multi-acid total digestion followed by ICP–MS–OES for over 50 elements. Gold and PGEs analyses were performed using FA–ICP–MS.

FIELD ACTIVITIES IN 2004

A total of 71 new sample sites were visited during the field season, resulting in the collection of 63 water samples, 19 peat samples, 24 stream sediment samples, 10 bedrock samples, 4 humus samples and 8 soil samples. Most of these samples were collected from 4 of the case study areas (Tib Lake, Cheeseman Lake, Right Angle Lake and Tarrison Lake). The primary objective of this sampling program was to extend sample coverage to areas outside of the influence of Cu-Ni-PGE mineralization and/or outside of Cu-Ni-PGE anomalous drainage catchments. The interpretation of geochemistry near mineralization and from within anomalous drainage catchments requires good characterization of background metal levels for comparison and contrast.

A further 30 sites, previously sampled in 2003, were revisited to collect check samples totalling 29 waters, 2 peats and 4 stream sediments. The emphasis on water check sampling was in part to investigate seasonal and/or perennial reproducibility and the effect of recent rainfall on metals geochemistry. Such factors may be an important consideration when utilizing hydrogeochemistry for mineral exploration.

Additional till sampling for heavy mineral concentrates (HMCs) to determine kimberlite indicator minerals (KIMs), metamorphic/magmatic massive sulphide indicator minerals (MMSIM®)[1] and gold grains was completed in the Lac des Iles study area (*see* Barnett, this volume).

PRELIMINARY RESULTS

Hydrogeochemistry Results and Quality Control

Table 51.1 contains summary statistics for several elements of particular interest to this project. The estimated precision of the Cu and Ni analysis shown in this table is based on the results of 20 field duplicates (precision estimates based solely on analytical splits achieved better numbers, as would be expected). In addition, the results for SLRS-4 indicate the high accuracy of the Cu and Ni analyses.

The direct analysis of Au, Pd and Pt by HR–ICP–MS to the parts per trillion (ppt) level represents a significant step forward for hydrogeochemical exploration. The precision estimates, again based on 20 field duplicates, are exceptional. In particular, the Pt results are very interesting, with a median level above detection limit and a range of data broader than that of Pd (Pd is more soluble than Pt). The estimated precision for Pt of one-tenth (0.1) of a ppt is astounding.

Spectral interferences on Pd (isotope ^{108}Pd was measured) occasionally required significant correction, therefore, it is possible that some loss or truncation of the true Pd geochemical signal has occurred. This may in part account for the tighter range of Pd data compared to the Pt data.

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[1] MMSIM is a registered trademark of Overburden Drilling Management Limited, Nepean, Ontario

Table 52.1. Results for several metals determined in waters and quality control data, including estimates of precision.

Element	Analytical Method[1]	Units	MDL[2]	Median Value of Unknowns n=226	Range		Estimated Precision[3]	SLRS-4 CRM [4] (n = 10)		
					Min	Max		Cert. Value	Mean	C.V. % [5]
Cu	ICP–MS	ppb	0.2	4.4	<0.2	148.6	±2	1.81	1.8	8.2
Ni	ICP–MS	ppb	0.3	1.2	<0.3	62.5	±1.5	0.67	0.7	20.1
Au	HR–ICP–MS	ppt	0.2	<0.2	<0.2	9.6	±0.5	n/a	0.9	142.6
Pd	HR–ICP–MS	ppt	1	<1	<1	24.0	±1	n/a	<1	0
Pt	HR–ICP–MS	ppt	0.1	0.2	<0.1	89.4	±0.1	n/a	1.0	17.0

Notes: [1] Analytical methods: ICP–MS = inductively coupled plasma mass spectroscopy; HR = high resolution.
[2] MDL = method detection limit.
[3] Estimated precision at 95% confidence level; based on results of 20 field duplicate pairs.
[4] SLRS-4 = National Research Council, Saint Lawrence River Standard #4: Certified Reference Material
[5] C.V.% = coefficient of variation at two standard deviations (95% confidence level)

Water Chemistry at Baker Zone, Lac des Iles Mine

As an elevated and exposed source of Cu-Ni-PGE mineralization, the Baker Zone is considered an excellent test case to study the hydromorphic dispersion of metals from a point source (e.g., Hattori and Cameron 2004). The spatial association of elevated Ni in waters around the Baker Zone (Figure 52.2) in this study is consistent with the findings of Hattori and Cameron (2004). In particular, the higher levels of Ni on the west side of Shorty Lake (closest to the Baker Zone) compared to the east side seems to indicate a higher geochemical flux due to the Baker Zone. The possibility of airborne dust contamination as a cause or contributing factor to the observed geochemical patterns, as discussed by Hattori and Cameron (2004), is discounted due to the different geochemistry on the east and west sides of the lake. It would be expected that both sides would be similarly effected if airborne fallout was a factor. However, another factor not previously considered is the tremendous amount of soil (till) that has been removed from the Baker Zone and washed off the top of the hill, presumably by high-powered water pumps. Significant gullies and/or gulches are present, notably at the northeast end of the Baker Zone leading towards the swamp at the north end of Shorty Lake. In fact, an erosion fence is in place to keep material from reaching Shorty Lake. This significant disturbance at the Baker Zone makes it less of an ideal case study site than previously thought, especially for use as an analogy to assist in exploration for new (undisturbed) mineralization.

The pattern of Pd in waters at the Baker Zone is shown in Figure 52.3. The high values on the Baker Zone came from water pumped from diamond-drill holes; water which is in direct contact with mineralization. The high levels near Camp Lake are likely related to proximity to contamination from the mine workings and roads (dust). The general lack of response on the flanks of the Baker Zone, in particular towards Shorty Lake, may be due to interception (fixation) by organic matter. The presence of anomalous Pd (13.6 ppb) in the lake sediment of Shorty Lake has previously been attributed to the Baker Zone mineralization, which lies approximately 100 m upslope to the west (Dyer and Russell 2002; Hattori and Cameron 2004). Shoreline traversing by the author in 2003 resulted in the discovery of mineralized bedrock on the northwest shore of Shorty Lake, within 6 m of the lake. A grab sample of gabbro from this outcrop, containing approximately 2% sulphides, returned 979 ppb Pd, 139 ppb Pt, 313 ppb Au, 2740 ppm Ni and 3960 ppm Cu. This occurrence is more likely the source of the lake sediment anomaly in Shorty Lake rather than the approximately 100 m distant Baker Zone.

Preliminary results suggest that hydromorphic dispersion of Pd is short; this may inhibit its usefulness, and in particular its cost-effectiveness for exploration, particularly if the metals Cu and Ni travel further and can be used successfully as pathfinders to PGE mineralization.

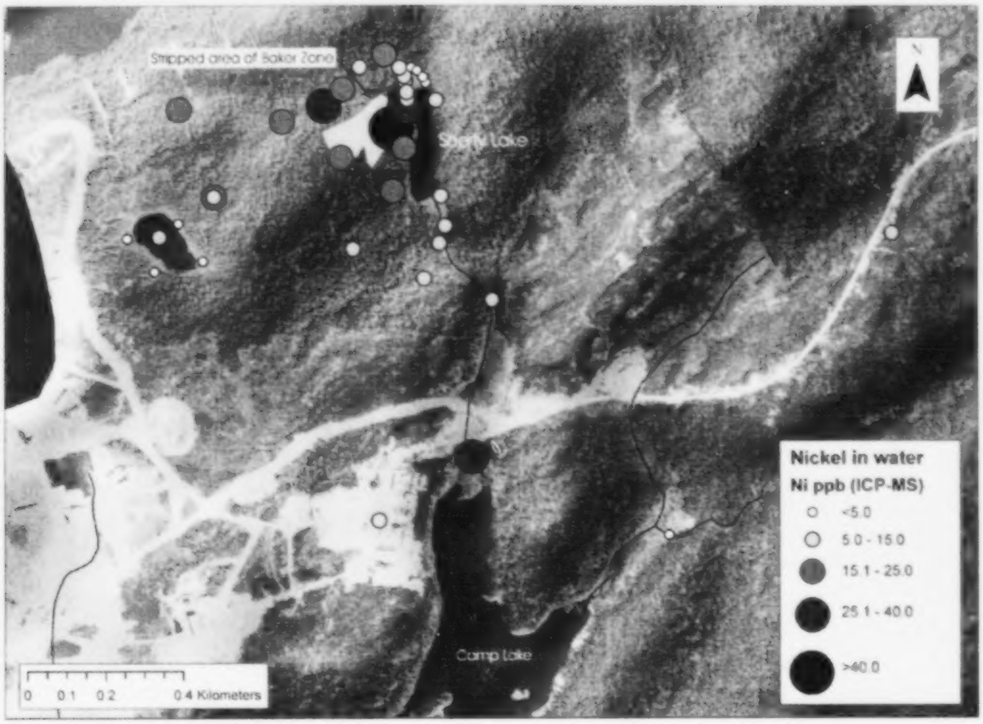
Stripped area of Baker Zone
N
Shorty Lake
Camp Lake
0 0.1 0.2 0.4 Kilometers
Nickel in water
Ni ppb (ICP-MS)
<5.0
5.0 - 15.0
15.1 - 25.0
25.1 - 40.0
>40.0

Figure 52.2. Nickel in water, Baker Zone area, Lac des Iles Mine.

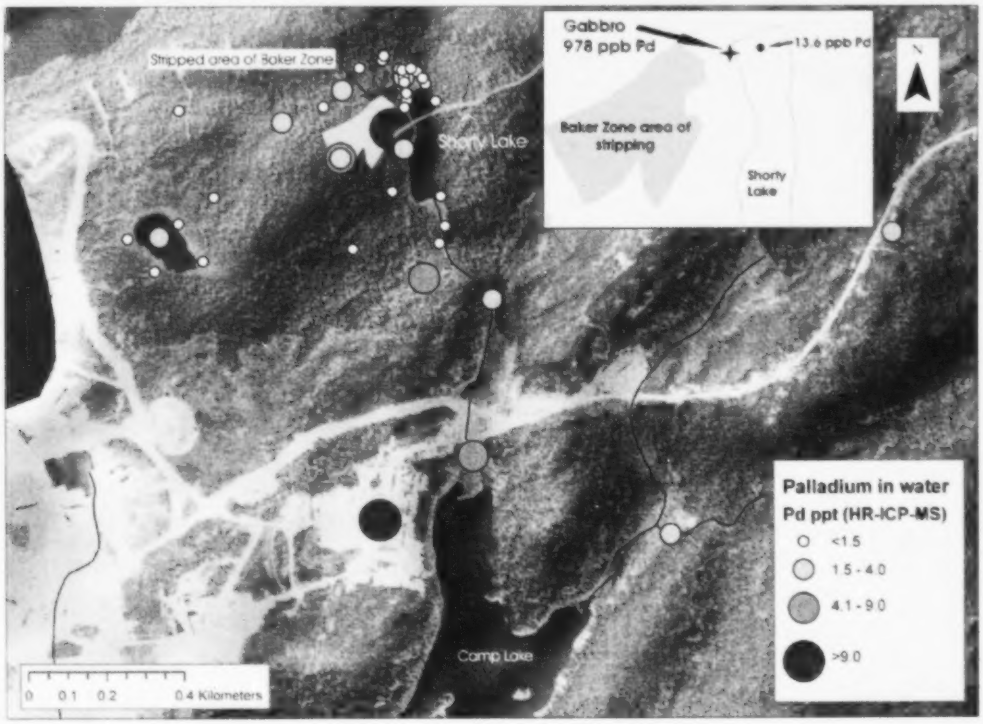
Stripped area of Baker Zone
Gabbro
978 ppb Pd
13.6 ppb Pd
Baker Zone area of stripping
Shorty Lake
N
Shorty Lake
Camp Lake
0 0.1 0.2 0.4 Kilometers
Palladium in water
Pd ppt (HR-ICP-MS)
<1.5
1.5 - 4.0
4.1 - 9.0
>9.0

Figure 52.3. Palladium in water, Baker Zone area and (inset) location of bedrock grab sample discussed in text.

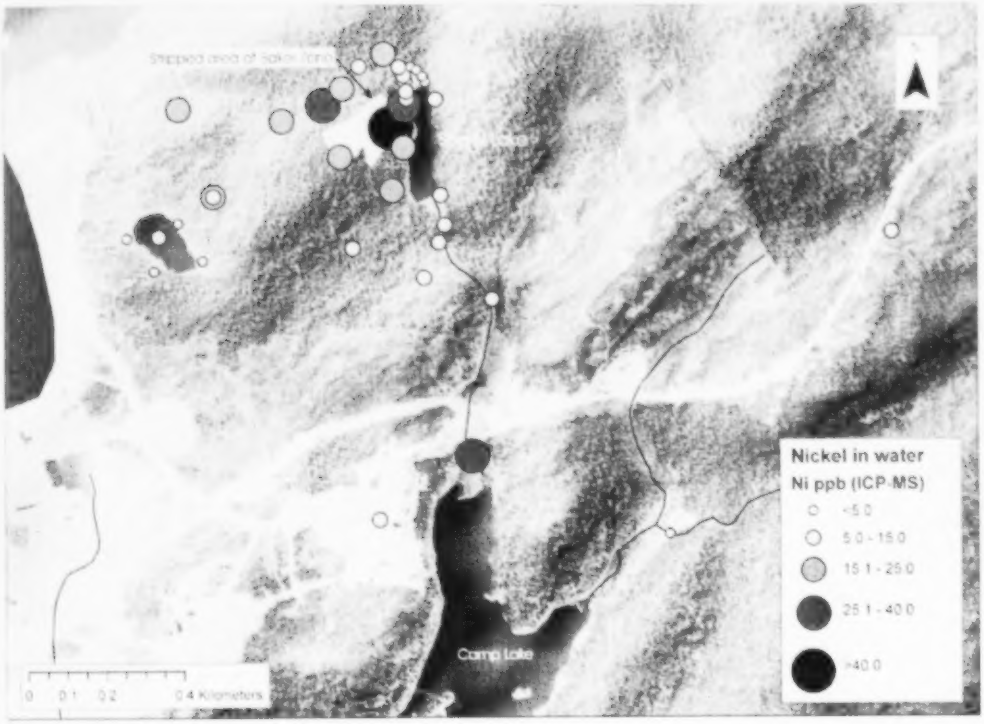
Stripped area of Baker Zone
Camp Lake
Nickel in water
Ni ppb (ICP-MS)
○ <5.0
○ 5.0 - 15.0
● 15.1 - 25.0
● 25.1 - 40.0
● >40.0
0 0.1 0.2 0.4 Kilometers

Figure 52.2. Nickel in water, Baker Zone area, Lac des Iles Mine.

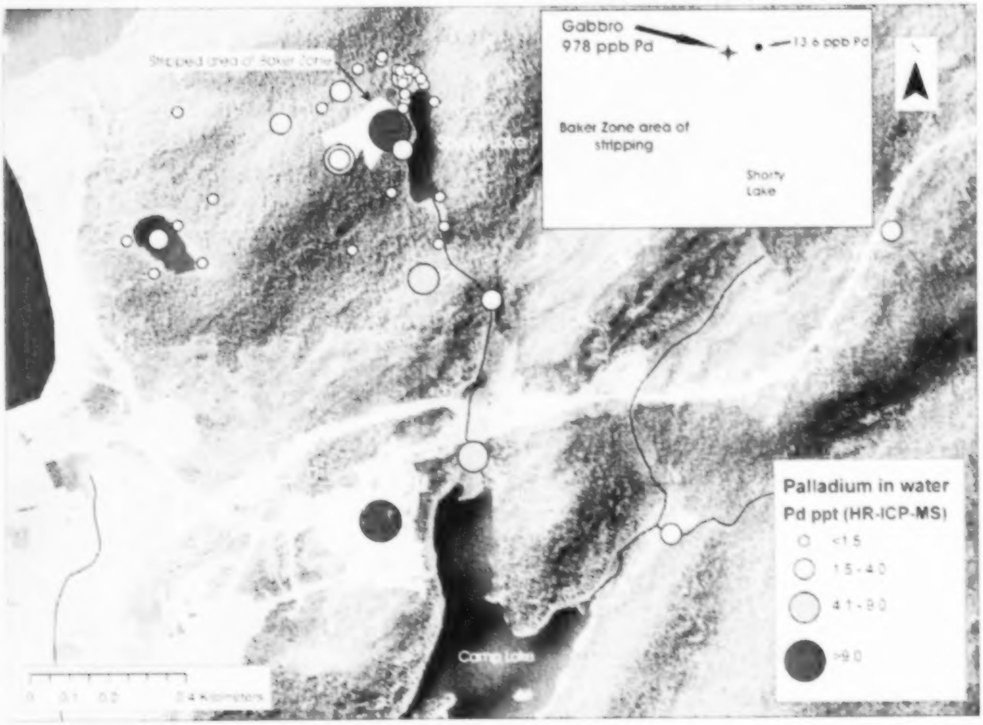
Gabbro
978 ppb Pd
13.6 ppb Pd
Baker Zone area of stripping
Shorty Lake
Stripped area of Baker Zone
Camp Lake
Palladium in water
Pd ppt (HR-ICP-MS)
○ <1.5
○ 1.5 - 4.0
○ 4.1 - 9.0
● >9.0
0 0.1 0.2 0.4 Kilometers

Figure 52.3. Palladium in water, Baker Zone area and (inset) location of bedrock grab sample discussed in text.

PROJECT STATUS

All samples collected during the 2004 field season were submitted for analysis during September and all laboratory analyses are expected by the end of October. Analysis of quality control data and incorporation of the new data with the 2003 season data sets will be followed by data plotting and interpretation. The final project report is expected to be completed and submitted to the LNRGI Science Advisory Committee in early 2005.

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53. Project Unit 04-022. Surficial Geology Mapping and Lake Nipigon Region Geoscience Initiative Lineament Study

P.J. Barnett[1]

[1]Sedimentary Geoscience Section, Ontario Geological Survey

INTRODUCTION

Field activities undertaken during the summer of 2004 were primarily aimed at obtaining a regional understanding of the distribution, properties and origin of Quaternary-age sediments within the Lake Nipigon area (Figure 53.1). This work is being done to assist in mineral exploration in the area and to be integrated with other data sets that are being produced as part of the Lake Nipigon Region Geoscience Initiative (LNRGI; *see* Rayner, this volume). Field observations and data collection were concentrated in the northern part of the region. Ground checking occurred within those areas covered by National Topographic System 1:50 000-scale maps: 52 H/02, 52 H/07, 52 H/11, 52 H/12, 52 H/14, 52 H/15, 52 I/02, 52 I/03, 52 I/06 and 52 I/07. Particular attention was paid to recording evidence of former ice flow directions. Surficial geology maps were created previously for the 5 LNRGI surficial geochemistry case studies project areas (Dyer, this volume). The current project's aim is to put these maps into a regional framework and provide surficial sediment information for areas not included in the case study project.

A small follow-up study, part of the LNRGI surficial geochemistry case study project, was undertaken to obtain data to better understand the dispersal pattern of heavy minerals in till in the Lac des Iles area. In addition, work towards a lineament analysis, within the overall LNRGI study area, began with the collection of pertinent data sets, developing appropriate methods and delineating some of the dominant lineaments (*see* Figure 53.1). The lineament analysis is being done with J. Shirota, Sedimentary Geoscience Section, Ontario Geological Survey.

FINDINGS

Two large landforms (moraines) previously identified in the study area (Zoltai 1965a, 1965b) mark former static positions of the glacier margin during deglaciation (Figure 53.2). The Kaiashk interlobate moraine formed, in part, between 2 lobes of the glacier. The Nipigon moraine formed at a later time along the margin of a lobe of ice situated within the Nipigon basin. During formation of the Nipigon moraine, a high-level proglacial lake fronted the glacier as indicated by the presence of large, expansive ice-marginal deltaic deposits. In contrast, Teller and Thorleifson (1983) suggested that waters flowing through the eastern outlets from glacial Lake Agassiz deposited these sediments except for surface deposits of wind blown sand. Both the Kaiashk and Nipigon moraines are composed primarily of thick deposits of sand and gravel that completely cover the bedrock surface, hindering mineral exploration in these areas. Subsequent erosion and redeposition of these moraine sediments by river and lake currents, as lower levels of proglacial lakes formed, has re-distributed sand and gravel to lower elevation plains; further obscuring the bedrock surface.

Summary of Field Work and Other Activities 2004,
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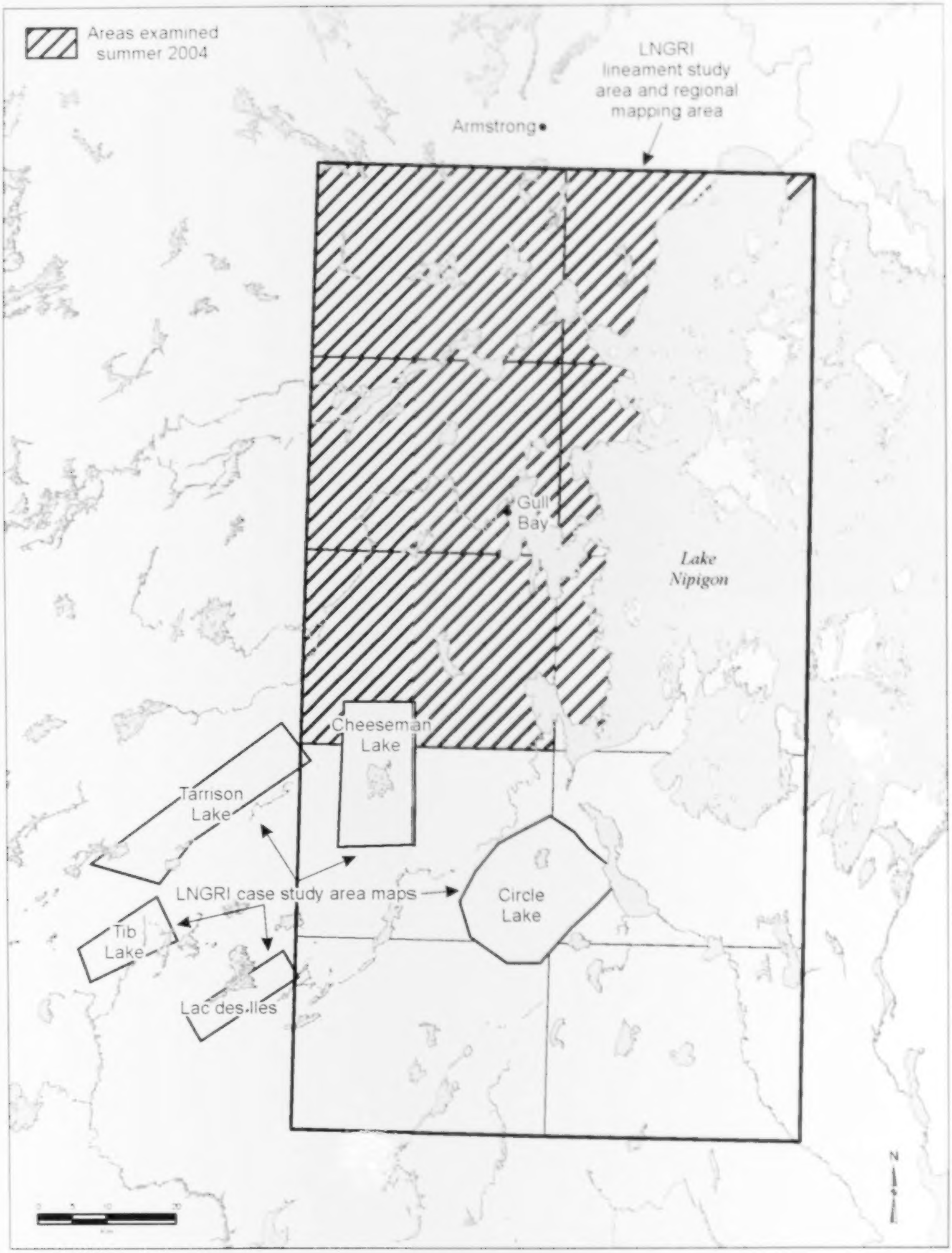
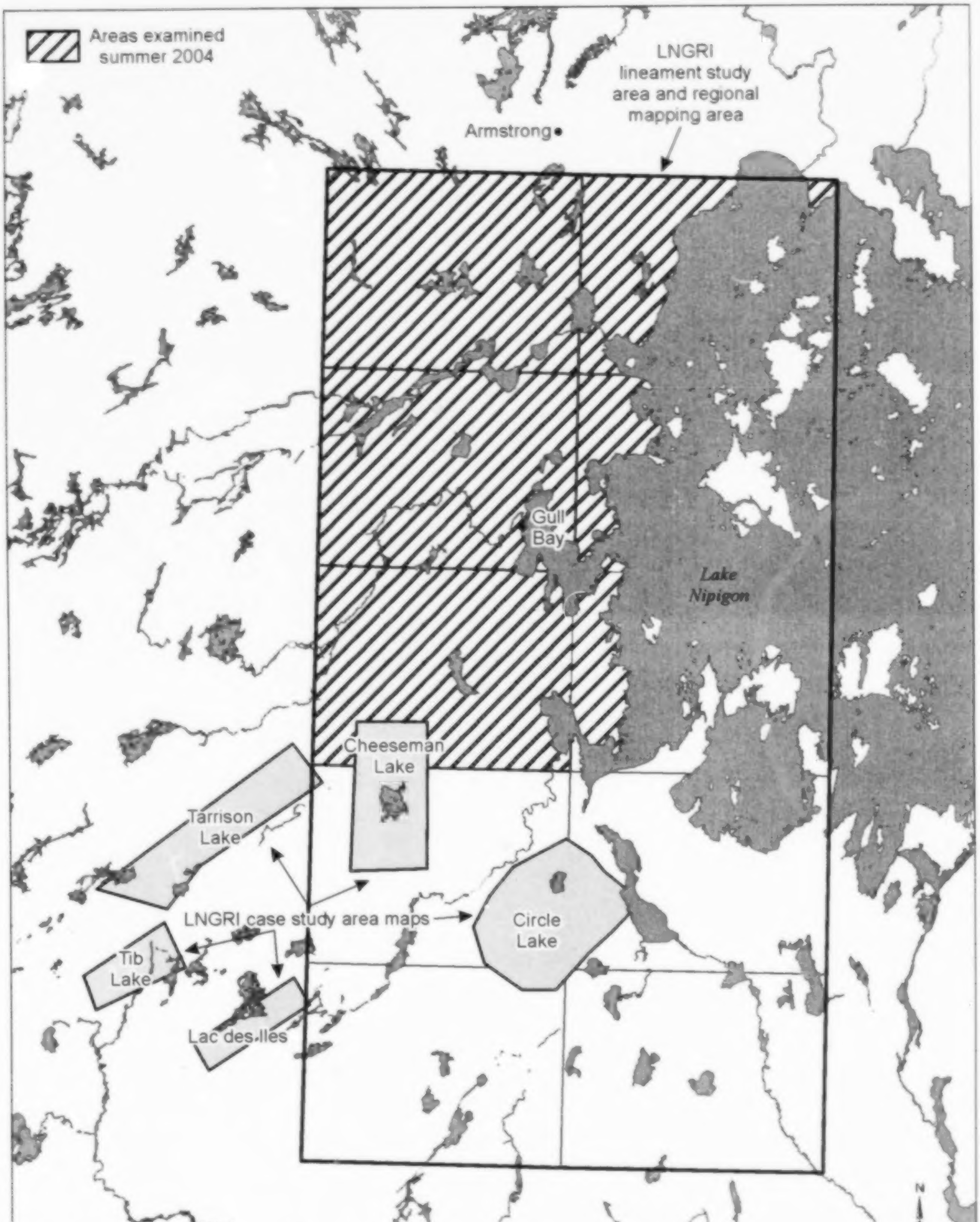

Areas examined summer 2004
LNGRI lineament study area and regional mapping area
Armstrong
Gull Bay
Lake Nipigon
Cheeseman Lake
Tarrison Lake
LNGRI case study area maps
Circle Lake
Tib Lake
Lac des Iles
0
5
10
20
N

Figure 53.1 . Location of the regional mapping project, the LNRGI Lineament Survey and the LNRGI Surficial Geochemical Case Study Project areas.



▨ Areas examined summer 2004
LNGRI lineament study area and regional mapping area
Armstrong
Gull Bay
Lake Nipigon
Cheeseman Lake
Tarrison Lake
LNGRI case study area maps
Circle Lake
Tib Lake
Lac des Iles
0 5 10 20
Km
N

Figure 53.1 . Location of the regional mapping project, the LNRGI Lineament Survey and the LNRGI Surficial Geochemical Case Study Project areas.

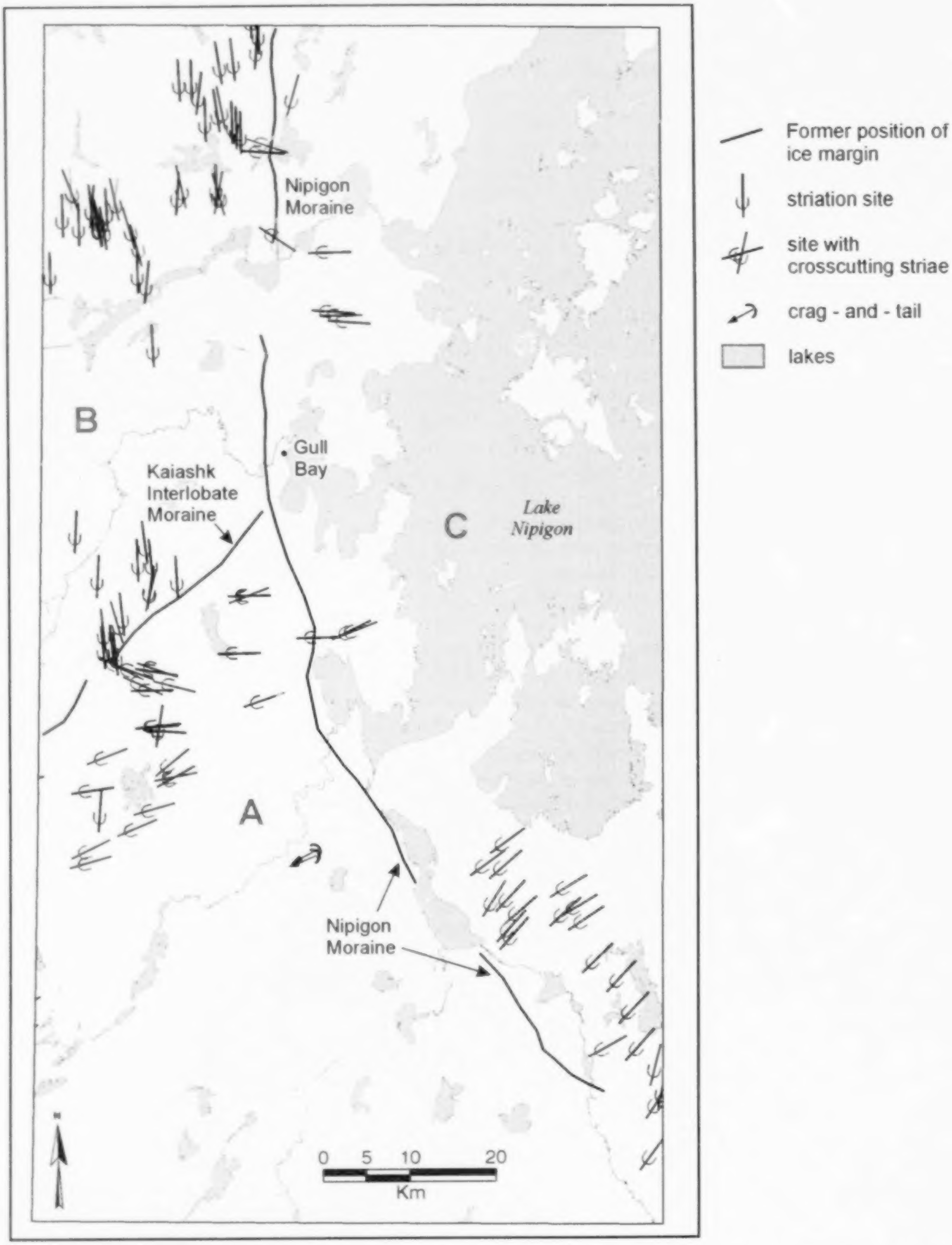

Nipigon Moraine
B
Gull Bay
Kaiashk Interlobate Moraine
C
Lake Nipigon
A
Nipigon Moraine
N
0 5 10 20
Km
Former position of ice margin
striation site
site with crosscutting striae
crag - and - tail
lakes

Figure 53.2. Distribution of striae data measured during the summer of 2004. A, B and C are zones with a similar records of ice movement or striation pattern (*see* text for explanation).

Ice flow directions measured this past summer are displayed in Figure 53.2. They are in general agreement with previously reported ice flow information for the area (Zoltai 1965a, 1965b; Mollard and Mollard 1983; Sado, Fullerton and Farrand 1994). The study area can be subdivided into 3 zones based on the preserved patterns of ice movement. The Kaiashk and Nipigon moraines and the study area limits form the boundaries of the zones. In zone A (*see* Figure 53.2), ice flow appears to have been initially southward, followed by an apparently strong flow toward the southwest and then a fanning of ice flow toward the west-northwest along the southern edge of the Kaiashk interlobate moraine. In zone B, ice flow is predominantly southward (*see* Figure 53.2). The Nipigon moraine marks the western border of zone C. In zone C, there appears to have been radial ice flow out of the Lake Nipigon basin up to the Nipigon moraine. There ice flow across the zone from north to south ranged from westward to southwestward to south-southwestward (*see* Figure 53.2).

Till is, for the most part, locally derived and can therefore be a useful medium for mineral exploration within the study area. It is commonly stony, having sand to silty sand matrix. It occurs as a thin, discontinuous cover overlying bedrock for a large part of the area mapped. Where thicker (>1 m), it may occur beneath undulating, drumlinized or fluted plains or within discontinuous ridges commonly between 3 to 5 m high that are covered in boulders. The boulder-covered ridges most likely represent minor standstills of the ice margin (minor moraines) that are commonly composed of subglacially transported debris.

Several exposures of subglacially deposited till overlying deltaic topset beds occur along Highway 527 north of Kopka Lake. This sequence of deposits indicates at least, a minor re-advance of the glacier from the east during formation of the Nipigon moraine in this area. Water levels in the Nipigon–Superior basin were also falling during the formation of this moraine.

It has been proposed that glacial Lake Agassiz drained eastward into the Nipigon–Superior basin (Elson 1957; Zoltai 1965a, 1967) through a network of 5 "channel complexes" referred to as the Kaiashk, Kopka, Pillar, Armstrong and Pikitigushi systems (Teller and Thorleifson 1983; Leverington and Teller 2003). Several of the proposed channels of the Kaiashk, Kopka and Pillar systems occur within the map area. Preliminary observations of landform relationships in the area of the proposed channel systems raises questions as to the validity of some of the relationships previously suggested (Teller and Thorleifson 1983; Leverington and Teller 2003). Some of the findings from the current work, related to eastern drainage of glacial Lake Agassiz, are discussed below. Agassiz drainage is not responsible for the carving of steep-walled channels cut into the diabase bedrock sills (Teller and Thorleifson 1983). These channels are commonly floored with subglacially deposited sediments or their remnants. Therefore, it is more likely that these large bedrock valleys were carved preglacially or subglacially or by a combination of both of these processes. Waters flowing indirectly from glacial Lake Agassiz via an intermediate lake likely carved the channels that contain the abandoned plunge pools identified by Teller and Thorleifson (1983). The well-defined channels (spillways) leading to the plunge pools were outlets of an intermediate level lake informally referred to as "glacial Lake Badour". In addition, the eastward drainage networks entered much higher level lakes in the Nipigon–Superior basin than suggested by Teller and Thorleifson (1983) and Leverington and Teller (2003). The earlier channels of the Kaiashk system entered lakes in the Nipigon–Superior basin at present-day elevations of about 355 m. Eastward drainage utilizing channels of the Pillar system entered lakes in the Nipigon–Superior basin above the levels reported by Teller and Thorleifson (1983) and Leverington and Teller (2003). Further evaluation of these outlets and their relationships to ice margins, glacial Lake Agassiz water planes and water levels in the Nipigon–Superior basin will occur during this study.

FUTURE WORK

Findings from field work carried out during 2004 provide important information and data critical to the understanding of the glacial history of the area and critical to the design and implementation of drift exploration programs in the area. Further work is planned for 2005 that will refine the glacial history and distribution of surficial deposits in the southern part of the Lake Nipigon Regional Surficial Mapping Program area.

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Geoscience Laboratories

54. Trace Element Analysis of Geological Samples by Inductively Coupled Plasma Mass Spectrometry at the Geoscience Laboratories: Revised Capabilities Due to Improvements to Instrumentation

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INTRODUCTION

Over the last 20 years, accurate and precise analyses of minor and trace elements in geological samples have become an increasingly important component of many industrial, government, and academic-based studies. In addition to requiring data for the transition elements (Sc to Zn), such studies increasingly demand accurate data for over 50 elements including the rare-earth elements (REE: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), high-field strength elements (HFSE: Ti, Zr, Nb, Hf, Ta, and/or Th and U), and large-ion lithophile elements (LILE: Rb, Sr, Cs, Ba, and Pb) for the interpretation of petrogenetic processes, tectonic environments, and the potential for economic mineralization (e.g., Kerrich and Wyman 1996).

Owing to the wide range of elements that can be analyzed by the technique from a single sample aliquot and its ability to determine accurately concentrations that range from sub-ppm up to sub-percent levels in many geological matrices, inductively coupled plasma mass spectrometry (ICP–MS) currently represents the most effective method of obtaining trace element data in geological samples and, over the last 10 years, has become the method of choice in many geochemical facilities, including the Geoscience Laboratories. Between the relocation of the Geoscience Laboratories to Sudbury in 1991 and the summer of 2003, the ICP–MS area has performed up to 20 000 trace element analyses per year, initially using 2 Perkin Elmer 5000 ICP–MS instruments and, later, using a single Perkin Elmer 5000 ICP–MS. Owing to the progressive failure of this instrument through the summer and autumn of 2003, last December, it was replaced with a Perkin Elmer Elan 9000 ICP–MS instrument and the existing trace element packages were transferred over to the new instrument through February and March of this year. Although the introduction of a new and more sensitive instrument has lead to greater reliability and improvements in the accuracy and reproducibility of trace element analyses obtained at the Geoscience Laboratories, the greater sensitivity required the modification of the 3 trace element packages routinely used for geological samples to incorporate an additional dilution stage and removal of the major elements from the list of analytes. This paper gives an overview of the changes that were made to the 3 packages and summarizes results obtained over the first 6 months of using the new instrument.

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TRANSFERRING THE ANALYTICAL METHODS

Three different instrumental packages were transferred to the new ICP–MS instrument:

1. A lithogeochemical package that focusses on the REE, LILE, and HFSE (method code: IM-101) in which the trace elements are calibrated against solutions made up from single or multi-elemental solution standards. The IM-101 ICP–MS package is designed as a specialized analysis for the accurate analysis of most common geological samples. Because more instrument time is spent per element and a number of corrections are applied for potential interferences, the data for these elements may be considered more accurate and precise than those obtained using the IM-100 package.
2. Two complete trace element packages (method code: IM-100) in which over 50 minor and trace elements are measured and calibrated against either digested rock standards (for rock digests, method codes CT4 (closed beaker) and OT4 (open beaker)) or acid-matrix-matched solutions made up from single or multi-elemental solution standards (for aqua regia leaches, method code ARD). The IM-100 ICP–MS package was originally designed as a general analysis to give accurate data for the minor elements and many of the more abundant trace elements and an estimate of the concentrations of the major elements (excluding Si, Na, and K) and some of the less abundant trace elements. Because many more elements are analyzed in the IM-100 package compared to the IM-101 package, and fewer corrections are applied, the precision and accuracy of the data for the less abundant trace elements is commonly inferior to those obtained from the more specialized IM-101 package.

Through the use of a dual-mode detector, in which individual ions are counted at low to moderate signal intensities (pulse-counting mode), but the total ion current is automatically measured at high signal intensities ($> 2 \times 10^6$ counts per second (cps)), the new ICP–MS instrument has the capacity to give a linear response for concentration variations of over more than 6 orders of magnitude. However, in order to avoid excess wear on the detector and the uncertainties associated with cross calibration of the 2 detector modes, analyses were designed to be performed in pulse-counting mode only and a limit of 2×10^6 cps placed on the signal. Because the ELAN 9000 ICP–MS instrument is significantly more sensitive than its predecessor, it was necessary to not only analyze samples at much greater dilutions than before, but also to review the isotopes used for each element (and selectively attenuate certain isotopes in order to ensure they remained in range). By performing additional dilutions before analysis, it was also possible to decrease the amount of sample build up within the instrument, decreasing maintenance time.

Owing to the differences in matrices, the set of elements to be determined, and the elemental concentration ranges between the 3 packages, separate optimizations had to be performed for each of the packages. However, the transfer of each method followed a similar procedure:

1. *Selection of isotopes:* The list of elements to be analyzed and isotopes to be used were already constrained by the elements currently listed for the IM-100 and IM-101 packages in the Geoscience Laboratories brochure. However, a number of alterations had to be made to accommodate the higher sensitivity of the instrument. The principle change to the packages was the removal of the major elements (in particular Al, Fe, Ca, Mg, P, and Mn) from the IM-100 package; these elements are all present at high concentrations in the samples solutions, yield intensities that are significantly higher than the desired upper limit, and can be analyzed better using inductively coupled plasma atomic emission spectrometry (ICP–AES) or X-ray fluorescence (XRF). Other changes included:
    i. For the IM-101 package: the addition of Ba and the monitoring of both ^{157}Gd and ^{160}Gd to determine which gave better data after correction of LREE oxide interferences.

ii. For the IM-100 package for digested samples: the addition of Bi, a change in the isotopes used to measure Mo and Cd (to ^{95}Mo and ^{111}Cd) to avoid potential interferences, and the removal of a number of elements that were being monitored, but not reported owing to the absence of values in the calibration materials (e.g., B, As, Rh, and Pt).

iii. For the IM-100 package for aqua regia leached samples: the addition of Ti, Se, Rh, In, Te, Ir, Pt, and Au (to be monitored to determine the feasibility of routine analysis), a change in the isotopes used to measure to Cu, Ga, Zr, Mo, Ag, Sn, Gd, and Re (to ^{65}Cu, ^{71}Ga, ^{90}Zr, ^{95}Mo, ^{107}Ag, ^{118}Sn, ^{160}Gd, and ^{187}Re) to avoid potential interferences and the addition of ^{77}Se to monitor and correct for plasma-based interferences on As.

2. *Sensitivity Test and Signal Attenuation*: The appropriate sample dilution factors and specific elements or isotopes that required dilution were determined by a comparison of the range of concentrations routinely observed in samples (as defined by the 10th and 90th percentiles of the concentrations of samples analyzed by each package during 2002-3) and the sensitivity of the instrument determined from the analysis of one or more standard solutions. These experiments showed that dilution by a factor of 10 on top of that used for the Elan 5000 was required for the analysis of the rock digests using either the IM-100 or IM-101 package (total dilution from rock to analyzed solution 1:5000), but that the aqua regia digests required a 1:20 dilution before analysis (total dilution factor, 1:2000). In each case, dilution was carried out with dilute (1% v/v) nitric acid made up from high-purity reagents. Because it was not anticipated that samples would be stored for long periods before analysis (being auto-diluted either on or off the instrument shortly before analysis), the long-term stability of the analytes in a less concentrated acid medium was not investigated.

   To keep signal intensities below the 2×10^6 cps cut-off, it was necessary to increase the resolution on the following elements in the 3 packages, thereby decreasing their signal intensities:
   For the IM-101 digestion package: Rb, Sr, Y, Zr, La, and Ce.
   For the IM-100 digestion package: Ti, Rb, Sr, Y, Zr, Ba, La, and Ce.
   For the IM-100 aqua regia leach package: Ti, V, Cr, Co, Rb, Sr, Y, Ba, La, Ce, and Pb (as well as changing to ^{62}Ni and ^{206}Pb from ^{60}Ni and ^{208}Pb).

3. *Determination of Sample Uptake and Washout Times*: Using either the trace element calibration solution or a sample high in the elements of interest, tests were run to determine the time taken for the signal intensity to stabilize after introduction of a solution to the instrument and for samples to wash out after analysis using different acid mixtures. Final washout times were chosen such that less than 5% carryover would be expected under the "worst case scenario" where adjacent solutions possess concentrations at the 90th and 10th percentiles of the observed range for each element. Although most elements were sufficiently removed after 60 to 90 seconds of washing in each of the analytical packages, some failed to decrease to the required levels within this time as a result of either the large range in concentrations possible in digested samples (e.g., Rb, Sr, Y, Cs, or the LREE) and/or a slow wash-out rate (e.g., Mo, Au, Hg, Bi, and Th). Rather than further increasing washout times, which would decrease overall sample throughput, it was decided to monitor for excessive contrasts in the concentrations these elements between adjacent samples and re-analyze when necessary.

RESULTS

Data obtained for procedural blanks, in-house and international reference materials over a six-month period from February to September 2004 are summarized in Tables 54.1 to 54.3.

Procedural Blanks and Detection Limit

For each analytical method, a conventional detection limit was calculated using the average concentration of the procedural blank plus three times its standard deviation. Prior to calculation of the detection limit, the blank data were screened for statistically anomalous values, which were excluded from the calculation. For most elements, the number of rejected data was relatively few (normally less than 5%) and could be linked to problems that arose during the initial work on the new packages. However, examination of the Cs concentrations obtained for digested samples by both the IM-100 and IM-101 packages showed a pronounced increase in the blank during the course of the study (average procedural blank increased from 2±4 to 63±18 ppb Cs). This increase was tracked to an anomalously Cs-rich batch of acid used during the initial sample digestion stage. Because the results obtained during the use of the contaminated acid are atypical of what may be expected for the technique, these data were not used in the estimation of the detection limit for Cs.

For almost all elements analyzed in the aqua regia digested samples, the estimated detection limits for the new instrument are significantly better than those previously available by the technique (commonly by a factor of 2 or better). However, for the samples analyzed after digestion, the improvements are less pronounced and the detection limits for many of the elements are either comparable or marginally higher. Much of this change can be attributed to a change in the way that the detection limit is calculated; the current calculations use both the average values of the blank and their variabilities, as oppose to only their variabilities. Exceptions to the general trends for the 3 packages are elements that either experience significant interference from the sample matrix (e.g., Sc, V, and Cr) or may be present as environmental contaminants in either the acid or water used for dilution (e.g., Cu, Zn, and Ni). The detection limits for these elements are generally a factor of 2 to 3 higher than before, despite efforts to minimize interferences through the reduction of acid concentrations and the use of cleaner water during the dilutions. Lower detection limits for these elements may be obtainable by increasing the signal to noise ratio by applying less dilution to the samples before analysis. However, this would result in a concomitant reduction in the working range for all elements in the package.

Instrument and Method Precision

Instrument and method precisions and overall method accuracy were assessed using data obtained for a suite of certified reference materials (CRM) and in-house standards covering the range of rock-types commonly analyzed by each package. In order to discriminate between variations arising from instrumental variations and those arising from variations during sample preparation, solutions prepared by the combination of multiple digestions of a number of certified reference materials were analyzed as part of each analytical run ("compiled" CRM data in Tables 54.1 to 54.3) and the data compared with those obtained for solutions of the same reference materials that were prepared with each batch of samples ("cycled" CRM data in Tables 54.1 to 54.3). Owing to the uncertainties known to arise from potentially incomplete digestion of resistant minerals during open-beaker digestions (Burnham et al. 2002), only data for samples digested by the closed beaker technique were considered in this study.

For the IM-101 and IM-100 analyses of digested samples, the reference materials included AGV-2 (andesite, USGS[2]), BHVO-2 (Hawaiian basalt, USGS), BIR-1 (Icelandic basalt, USGS), GSP-2 (granodiorite, USGS), GSR-1 (biotite granite, IGGE), GSR-2 (hornblende andesite, IGGE), GSR-3 (olivine basalt, IGGE), NBS-688 (basalt, NIST), RGM-1 (rhyolite, USGS), STM-1 (nepheline syenite, USGS), and SY-4 (diorite gneiss; CCRMP). Additional information on the reproducibility of analyses was obtained by the analysis of 4 in-house reference materials: LKNIP-1 (basalt from the Lake Nipigon area, Ontario), MRB-29 (Keweenawan basalt from the Black Bay Peninsula, Ontario), MRB-32 (weakly Ni-sulphide mineralized peridotite from the Kanichee Mine, near Temagami, Ontario), and NPD-1 (Nipissing diabase from the Cobalt–Temagami area, Ontario). For the IM-100 analyses of aqua regia leached samples, the reference materials included 4 lake sediments (LKSD-1 to LKSD-4: CCRMP), 4 stream sediments (STSD-1 to STSD-4: CCRMP), and 4 till samples (TILL-1 to TILL-4: CCRMP). Because many of these materials were originally certified prior to the availability of accurate data for many elements at low concentrations, their certificates contain proposed or information values for many of the elements of interest (with large uncertainties) or may be missing values altogether. Where additional, potentially more precise and/or accurate trace element data could be found, these are presented for comparison in Tables 54.1 to 54.3.

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[2] CRM issuing bodies: USGS: United Sates Geological Survey, USA. IGGE: Institute of Geophysical and Geochemical Prospecting, People's Republic of China. NIST: National Institute of Standards and Technology, USA. CCRMP: Canadian Certified Reference Materials Project, Canada.

INSTRUMENT PRECISION

The Geoscience Laboratories aim to provide analytical results whose accuracy and precision are better than ±10% (2σ) for element concentrations exceeding the limit of quantification (LLoQ)[3] for the method. Examination of the data for the compiled solutions analyzed by each of the methods transferred onto the new instrument indicate that the instrumental precision reaches this target for most elements and in many cases exceeds it.

For the IM-101 analysis of digested samples, the instrumental precision of almost all elements was better than ±5% (2σ) for either all or 5 of the 6 compiled solutions where the elements were above the LLoQ. Where the concentrations approached the LLoQ (e.g., for Zr, Ba, La, and Pr in the trace-element poor basalt standard BIR-1, or Eu in the rhyolite standard RGM-1), the error increased to between 5 and 8.5%. Only Rb showed consistently poorer than 5% precision (±6 to 7%, 2σ).

For the IM-100 analysis of digested samples, the instrumental precisions for most of the REE, HFSE, and LILE (including Rb) were similar to those observed for the IM-101 package and generally better than ±5% (2σ). Of the other elements, most attained the target precision of better ±10% (2σ) in the majority of the solutions, increasing to 15% at lower concentrations (e.g., Li in BIR-1, or Zn in AGV-2, BIR-1 and GSR-2). The instrumental precisions for Cd, Sn, and Be were generally poorer than the target value (more than half of the compiled solutions for reference materials with suitable concentrations exhibited more than 10% variation), presumably as a result of the large uncertainty introduced by the low concentrations of these elements in the reference materials used for calibration. Work to revise the choice of calibration materials to constrain these elements better is currently under way. The concentrations of Cr, Mo, Sb, Ta, W, and Bi in most of the reference materials used for the compiled solutions were too low for the instrumental precision to be constrained for these elements.

For the IM-100 analysis of aqua regia leached samples, the instrument precision for most elements present at suitable concentrations was better than ±10% (2σ) in almost all samples. Exceptions include Be, Hf, Ta, Hg, for which the instrumental precision was between 10 and 20% for most of the reference materials. Hf, Ta, and Hg, as well as Zr, Ag, and Au also showed very poor precision (± >20%) for at least 1 of the 8 compiled solutions. Because the concentrations of V, Te, and the precious metals in the reference materials were generally less than their estimated limits of quantification, it was not possible to estimate reliable instrumental precisions for these elements. The reproducibility of the other 3 elements that are being investigated as possible additions to the package ranged from excellent (Ti and In, better than ±10% 2σ in all 8 materials) to poor (Se, 13–19% 2σ in the 3 materials possessing concentrations above the LLoQ).

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[3] Limit of quantification (LLoQ) defined as the mean procedural blank plus ten time its standard deviation.

METHOD PRECISION

The overall precision of the 3 analytical methods can be assessed from the reproducibility of the analyses of the reference materials that were cycled through as quality assurance monitors during sample analysis. In general, the variability in the results for each of the elements analyzed by the 3 methods show similar trends to those found for the instrumental precisions, but are generally higher, presumably as a result of sample heterogeneity. Although such factors require investigation, their discussion is beyond the scope of this paper.

Accuracy

The accuracies of the transferred methods were estimated by regression of the concentrations determined for the 10 reference materials that were cycled through as quality assurance monitors during sample analysis against the certificate values for these materials. Where values were missing or poorly constrained in the original certificates, the measured values were compared to data from recently published compilations (e.g., Hall and Pelchat 1997; Lynch 1997, 1999; Liang and Gregoire 2000; Raczek et al. 2000; Yu et al. 2000; Dulski 2001). Because the material with the highest concentration commonly dominated the regressions, an unrepresentatively high bias (either positive or negative) was obtained for a number of elements where the measured concentration for this material deviated significantly from the certificate value. In many cases (e.g., Li in GSR-1 or Nd in GSP-2), the disagreement can be accounted for by either poor precision and/or accuracy in the certificate value and better agreement is found with the more recently published values. However, where recent values were not immediately available (e.g., Zn in STM-1, Cd in STM-1, Tl in GSR-1, or Tl and Pb in GSP-2), it was not possible to determine whether the anomalous values for these individual materials were the result of bias at high concentrations or errors in the certificate values.

In general, the concentrations determined for the reference materials using the IM-101 method indicated less than ±5% bias (i.e., better than 5% accuracy) for almost all elements (the exceptions being Tb (biased ~7% low) and Th, and U (biased ~7% high)), consistent with the ±10% target accuracy for the method.

The concentrations determined for the reference materials using the IM-100 method show similar accuracies to those of the IM-101 method, with most elements within the ±10% target range. However, the confirmation of the accuracies of a number of elements was hampered by poorly constrained (or possibly inaccurate) certificate values for some elements (see above). Of the 44 elements analyzed by the IM-100, only Ti, Ni, and Sb showed a systematic bias (~11% low, 11% high and 12% low, respectively) for more than one reference materials with higher concentrations.

For a number of reasons, the accuracy of the IM-100 analyses of aqua regia leached samples could only be tested for a limited number of elements. Firstly, appropriate certificate data are available for only 13 of the 54 elements analyszd by the IM-100 method in the aqua regia leached samples. Secondly, with the exception of Sr and Ba in the LKSD and STSD sample series (Lynch 1997), few data are available from other sources for the concentrations of the other elements that can be extracted by hot concentrated nitric-hydrochloric acid mixtures. Finally, the amount of each element that can be extracted from a sample is highly dependant on details of the extraction method (which can vary substantially between laboratories). Of the elements for which certificate and/or other reference data are available for either all 12 or 8 of the 12 reference materials, most (e.g., Cr, Co, Ni, Cu, Zn, As, Mo, Ag, Cd, Ba, Hg, Pb, and Bi) show less than 10% bias. Of the remaining elements, both V and Ti appear to be highly variable and biased low at all concentrations, whereas Sb appears to change from being biased low at low concentrations to high at high concentrations. For V and Ti, the poor accuracy (and method precisions) is inferred to arise from the high background intensities present during analysis owing to plasma-based interferences coupled with variable recoveries during solution preparation and indicates that better background corrections may be required. The anomalous behaviour of Sb can be attributed to the more aggressive nature of the aqua regia attack used at the Geoscience Laboratories relative to those used during the certification of the reference materials: larger volumes of acid are used at the Geoscience Laboratories (4 mL HCl and 3 mL HNO_3 versus a total of 4 mL HCl and HNO_3) and the acids spend more time in contact with the samples. As a consequence, the measured Sb concentrations correspond more closely to their "total" Sb contents as given in the certificates and corroborated by hydride-generation ICP–MS (Hall and Pelchat 1997). Although the Se concentrations determined in the reference materials are relatively unbiased relative to the values obtained by Hall and Pelchat (1997), they appear to be consistently high by ~ 0.45 ppm owing to uncorrected interference from $^{164}Dy^{2+}$ on $^{82}Se^{+}$ (which may also be responsible for the poor precision of the measurements). Although the Se intensities are now corrected for this interference, at this time, insufficient data have been produced by this method.

Method Upper Limits

In the absence of sufficient data obtained using both pulse-counting and analog-mode detection methods for most elements, provisional upper limits for each element in the 3 analytical methods were estimated for analysis in pulse-counting mode only using the measured sensitivity of the instrument for each element and the maximum intensity attainable by the detector in this mode (2×10^6 cps: Table 54.4)[4]. For most elements, these concentrations are considerably higher than the range commonly encountered in non-mineralized geological samples, indicating that saturation of the detector should not normally be a limiting factor in their determination, despite the higher sensitivity of the instrument. However, the intensities of a few elements in some of the reference materials used in each package did approach or exceed the upper limit for pulse counting (e.g., Ti, V, Cr, Cu, Ni, Rb, Zr, Nb, and Th in digested rock samples and Ba, La, Ce, W, Bi, and U in aqua regia leached samples). In such cases, it was observed that for most elements, cross-calibration of the detectors allowed successful correction of the over-range intensities; where certificate or reference values were available for the elements, data obtained in analog mode were found to be accurate and/or in good agreement with data obtained in pulse-counting for either the same original sample material or the same sample solution. Over the coming months, the accuracy of analyses of samples possessing high concentrations of many of the more abundant trace elements and/or base metals will be further tested through the preparation and analysis of a suite of appropriate trace element rich reference materials and continued participation in the Proficiency Testing Program for Mineral Analysis Laboratories (PTP–MAL).

SUMMARY

The results obtained over the first 6 months of using the new Perkin Elmer Elan 9000 ICP–MS for the analysis of trace elements in geological samples indicate that the quality of the data matches, and frequently exceeds, that targeted at the Geoscience Laboratories, with precisions and accuracies better then 10% for most elements.

As a result of the increase in instrument sensitivity, a number of elements (in particular the major elements) have been removed from the IM-100 package for both digested and aqua regia leached samples and the working of ranges of many elements have changed slightly. Although the lower limits of detection for each element in the 3 trace element packages have been determined through the analysis of the procedural blanks, the upper limits for most elements have yet to be constrained, especially if analyses can be carried out using signal detection in both pulse-counting and analog modes, as appear to be the case. Further work on this issue is required. Despite the apparent change in the capabilities of the instrument, modification of the working ranges used during the reporting of data will need to wait until the introduction of the new laboratory information management system (LIMS) in spring 2005 and will coincide with an overhaul of all methods in use at the Geoscience Laboratories.

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[4] Because the sensitivity of the instrument varies slightly on a day-to-day basis, the calculations in Table 54.4 represent conservative estimates of the instrumental upper limits based on the maximum sensitivity shown over the last 6 months.

Initial work on the analysis of 6 additional elements in solutions after aqua regia leaches showed that it should be possible to determine In and Te with reasonable accuracy and/or reproducibility when the elements are present at moderate concentrations in rocks samples (>100 ppb Te, >20 ppb In), but that further work on the correction of interferences on Se was required in order to produce the most accurate data. Owing to the low concentrations of the 3 precious metals added to the aqua regia package (Rh, Ir, and Pt) and the absence of certificate or reference values for these elements in the reference materials used for quality assurance in the aqua regia package, it has not been possible to determine the efficacy of such analyses on the new instrument.

Further details of analytical services and methods available at Geoscience Laboratories may be obtained by contacting the Client Services Representative at 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5; Telephone: (705) 670-5637; toll free: 1-866-436-5227; e-mail: geoscience.labs@ndm.gov.on.ca; web site http://www.mndm.gov.on.ca/mndm/mines/labs/labintroe.htm.

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Notes for Table 54.1:

Italics: Elements added to the IM-100 or IM-101 package for digested samples.
Underlined: Data obtained for analyses on the analog detector only.
1) LLoD defined as the average blank plus 3 standard deviations.
2) Uncertainties on analyses and certified/reference values indicate 2 standard deviations.
3) Numbers in brackets indicate the number analyses used in the average.
4) Reference data from Raczek et al. (2001)
5) Reference data from Dulski (2001)
6) Reference data from Liang and Gregoire (2000)
7) Ta and W reference data from Korotev (1996)
8) An average value of 495 ± 65 ppm Rb was determined for six (6) analyses performed on the analog detector.
9) A value of 289 ppm Nb was determined for a single analysis performed on the analog detector.
10) Cs data only given for cycled samples prepared using low-Cs perchloric acid.
11) A value of 111 ± 9 ppm Th was determined for five (5) analyses performed on the analog detector.
12) A value of 58 ± 7 ppm Th was determined for two (2) analyses performed on the analog detector.

Notes for Table 54.2:

Italics: Elements added to the IM-101 package for digested samples.
Underlined: Data obtained for analyses on the analog detector only.
1) LLoD defined as the average blank plus 3 standard deviations.
2) Uncertainties on analyses and certified/reference values indicate 2 standard deviations.
3) Numbers in brackets indicate the number analyses used in the average.
4) Reference data from Raczek et al. (2001)
5) Reference data from Dulski (2001)
6) Mo, Tl, and Bi reference data from Yu et al. (2000)
7) Reference data from Liang and Gregoire (2000)
8) Ta and W reference data from Korotev (1996)
9) A value of 14 630 ± 1050 ppm Ti was determined for three (3) analyses performed on the analog detector.
10) A value of 12 450 ± 1525 ppm Ti was determined for two (2) analyses performed on the analog detector.
11) A value of 11 795 ± 635 ppm Ti was determined for nine (9) analyses performed on the analog detector.
12) A value of 10 324 ± 880 ppm Ti was determined for twenty-one (21) analysis performed on the analog detector.
13) A value of 327 ppm V was determined for a single analysis performed on the analog detector.
14) A value of 1365 ± 54 ppm Zr was determined for three (3) analyses performed on the analog detector.
15) A value of 274 ± 15 ppm Nb was determined for two (2) analyses performed on the analog detector.
16) Cs data only given for cycled samples prepared using low-Cs perchloric acid.
17) A value of 108.7 ppm Th was determined for a single analysis performed on the analog detector.

Notes for Table 54.3:

Italics: Elements added to the IM-100 package for aqua regia leached samples.
Underlined: Data obtained for analyses on the analog detector only.
1) LLoD defined as the average blank plus 3 standard deviations.
2) Uncertainties on analyses and certified/reference values indicate 2 standard deviations.
3) Numbers in brackets indicate the number analyses used in the average.
4) Reference data for concentrated HCl – concentrated HNO_3 leach from Lynch (1997, 1999)
5) Reference data for **total** As, Se, Sb, Te, and Bi from Hall and Pelchat (1997)
6) An average value of 1330 ± 40 ppm Ba was determined for three (3) analyses performed on the analog detector.
7) An average value of 103.8 ± 9.3 ppm Ce was determined for three (3) analyses performed on the analog detector.
8) A value of 99.7 ppm Ce was determined for a single analysis performed on the analog detector.
9) A value of 32.8 ppm U was determined for a single analysis performed on the analog detector.
10) An average value of 32.2 ± 1.3 ppm U was determined for four (4) analyses performed on the analog detector.

Table 54.1. Summary of trace element data obtained on the Elan 9000 ICP–MS using the IM-101 package (after closed-beaker digestion).

		Rb	Sr	Y	*Zr*	Nb	Cs[10]	*Ba*	La	Ce	Pr	Nd	Sm
Procedural Blanks													
	Average	0.06	0.2	0.02	1	0.01	0.0020	*0.3*	0.02	0.04	0.005	0.02	0.005
	±	0.11	1.0	0.042	1.5	0.023	0.0027	*0.39*	0.047	0.09	0.011	0.038	0.009
	n	133	143	144	144	137	43	*140*	142	142	142	142	143
	LLoD[1]	0.23	1.7	0.083	3.2	0.044	0.006	*0.88*	0.091	0.18	0.021	0.077	0.018
Inter-Laboratory Reference Materials													
AGV-2	**Cycled**	70.6 ± 1.9[2] (5)[3]	660 ± 40 (5)	19.0 ± 1.3 (5)	240 ± 11 (5)	13.9 ± 0.3 (5)	1.190 ± 0.025 (3)	*1,142 ± 26 (5)*	39.5 ± 2.3 (5)	72 ± 5 (5)	8.4 ± 0.7 (5)	31.9 ± 3.1 (5)	5.7 ± 0.5 (5)
	Compiled	70 ± 4 (34)	664 ± 30 (34)	19.1 ± 0.8 (34)	242 ± 10 (34)	14.0 ± 0.4 (34)	1.18 ± 0.04 (34)	*1,150 ± 30 (34)*	39.1 ± 1.1 (34)	71.8 ± 1.8 (34)	8.42 ± 0.26 (34)	31.8 ± 1.0 (34)	5.66 ± 0.16 (34)
	Certificate	68.6 ± 4.6	658 ± 34	20 ± 2	230 ± 8	15 ± 2	1.16 ± 0.16	*1,140 ± 64*	38 ± 2	68 ± 6	8.3 ± 1.2	30 ± 4	5.7 ± 0.6
	Reference[4]	66.3 ± 0.4	661 ± 1.3					*1,130*	37.9 ± 0.4	68.6 ± 0.5	7.68	30.5 ± 0.1	5.49 ± 0.02
BHVO-2	**Cycled**	9.6 ± 0.6 (10)	400 ± 19 (10)	25.6 ± 1.1 (10)	178 ± 10 (10)	18.4 ± 1.0 (10)	0.108 ± 0.013 (4)	*133 ± 6 (10)*	16.0 ± 0.8 (10)	39.4 ± 1.8 (10)	5.61 ± 0.25 (10)	26.0 ± 1.2 (10)	6.34 ± 0.31 (10)
	Certificate	9.8 ± 2.0	389 ± 46	26 ± 4	172 ± 22	18 ± 4		*130 ± 26*	15 ± 2	38 ± 4		25.0 ± 3.6	6.2 ± 0.8
	Reference[4]	9.08 ± 0.06	396 ± 0.8					*131.0*	15.2 ± 0.1	37.5 ± 0.1	5.29 ± 0.05	24.5	6.07 ± 0.01
BIR-1	**Cycled**	0.29 ± 0.25 (10)	107 ± 23 (10)	14.9 ± 2.0 (10)	16.1 ± 1.9 (10)	0.55 ± 0.05 (10)	0.006 ± 0.004 (5)	*6.9 ± 0.7 (10)*	0.70 ± 0.08 (10)	2.02 ± 0.18 (10)	0.40 ± 0.03 (10)	2.53 ± 0.19 (10)	1.14 ± 0.07 (10)
	Compiled	0.35 ± 0.13 (34)	110 ± 5 (34)	15.4 ± 0.6 (34)	18.0 ± 1.0 (34)	0.55 ± 0.03 (34)	0.013 ± 0.005 (34)	*6.7 ± 0.4 (25)*	0.69 ± 0.06 (34)	2.02 ± 0.10 (34)	0.40 ± 0.03 (34)	2.52 ± 0.10 (34)	1.14 ± 0.05 (34)
	Certificate		108 ± 4	16 ± 2	18 ± 2	0.6		*7*	0.62 ± 0.14	1.95 ± 0.80		2.5 ± 1.4	1.1
	Reference[5]	0.36 ± 0.05	110 ± 4.5	14.9 ± 0.5	15.4 ± 0.8		0.0099 ± 0.0004	*6.4 ± 0.7*	0.62	1.89 ± 0.05	0.39 ± 0.01	2.35 ± 0.1	1.08 ± 0.05
GSP-2	**Cycled**	248 ± 16 (6)	236 ± 16 (6)	25.3 ± 2.2 (6)	550 ± 60 (6)	26.6 ± 1.6 (6)	1.20 ± 0.04 (4)	*1,310 ± 120 (6)*	190 ± 15 (6)	440 ± 60 (2)	57 ± 6 (6)	214 ± 21 (6)	26.7 ± 2.7 (6)
	Certificate	245 ± 14	240 ± 20	28 ± 4	550 ± 60	27 ± 4	1.2 ± 0.2	*1,340 ± 88*	180 ± 24	410 ± 60	51 ± 10	200 ± 24	27 ± 2
	Reference[4]	242 ± 1.5	238 ± 1.2					*1340 ± 10.7*	186 ± 0.6	445 ± 1.3	50.7	207 ± 0.8	26.2 ± 0.1
GSR-1	**Cycled**	480 ± 40 (20)[8]	110 ± 6 (26)	66 ± 7 (26)	171 ± 18 (22)	43.5 ± 2.3 (26)	38.4 ± 1.4 (5)	*335 ± 14 (26)*	56.3 ± 2.4 (26)	116 ± 5 (26)	13.2 ± 0.6 (26)	47.4 ± 1.9 (26)	10.1 ± 0.4 (26)
	Certificate	466 ± 10	106 ± 3	62 ± 2	167 ± 5	40.0 ± 1.4	38.4 ± 0.8	*343 ± 13*	54 ± 2	108 ± 4	12.7 ± 0.5	47 ± 2	9.7 ± 0.5
	Reference[6]	453 ± 15	112 ± 2	67.8 ± 1.7	152 ± 8	44.2 ± 0.9	38.8 ± 0.7	*315 ± 9*	53.9 ± 1.2	112 ± 3	12.8 ± 0.3	44.3 ± 1.0	9.69 ± 0.08
GSR-2	**Cycled**	38 ± 5 (21)	820 ± 50 (21)	8.6 ± 0.8 (21)	96 ± 6 (21)	5.6 ± 1.2 (21)	1.76 ± 0.07 (5)	*1,020 ± 70 (21)*	21.6 ± 2.8 (21)	41 ± 5 (21)	4.8 ± 0.6 (21)	18.6 ± 2.1 (21)	3.3 ± 0.3 (21)
	Compiled	39.0 ± 2.3 (33)	820 ± 40 (33)	8.74 ± 0.32 (33)	97 ± 4 (33)	5.99 ± 0.14 (33)	1.76 ± 0.05 (33)	*1,019 ± 25 (33)*	22.0 ± 0.7 (33)	42.3 ± 1.3 (33)	4.88 ± 0.13 (33)	18.9 ± 0.6 (33)	3.39 ± 0.12 (33)
	Certificate	37.6 ± 1.7	790 ± 16	9.30 ± 0.50	99 ± 5	6.8 ± 0.7	2.3 ± 0.4	*1,020 ± 21*	21.8 ± 1.0	40 ± 2	4.9 ± 0.2	19 ± 1	3.4 ± 0.1
	Reference[6]	33.0 ± 1.2	785 ± 15	8.71 ± 0.06	93.0 ± 1.2	5.46 ± 0.05	1.63 ± 0.03	*990 ± 8*	20.6 ± 0.3	40.3 ± 0.7	4.65 ± 0.05	17.5 ± 0.1	3.11 ± 0.10
GSR-3	**Cycled**	39.3 ± 2.3 (15)	1,160 ± 70 (15)	22.9 ± 1.3 (15)	300 ± 17 (15)	76 ± 4 (15)	0.435 ± 0.017 (4)	*544 ± 32 (15)*	57 ± 3 (15)	112 ± 6 (15)	13.1 ± 0.7 (15)	53.2 ± 3.0 (15)	10.5 ± 0.5 (15)
	Compiled	38.2 ± 2.5 (32)	1,120 ± 50 (32)	22.2 ± 0.8 (32)	291 ± 12 (32)	74.5 ± 2.0 (32)	0.45 ± 0.02 (32)	*534 ± 15 (32)*	56.7 ± 1.6 (32)	110 ± 4 (32)	12.9 ± 0.4 (32)	52.3 ± 1.7 (32)	10.3 ± 0.4 (32)
	Certificate	37 ± 2	1,100 ± 30	22 ± 1	277 ± 10	68 ± 4	1.20	*526 ± 12*	56 ± 2	105 ± 5	13.2 ± 0.8	54 ± 2	10.2 ± 0.3
	Reference[6]	39.9 ± 0.5	1,155 ± 32	23.9 ± 1.1	275 ± 11	75.8 ± 3.2	0.45 ± 0.02	*541 ± 12*	58.9 ± 2.1	113 ± 4	13.4 ± 0.5	52.5 ± 1.8	10.4 ± 0.4
NBS-688	**Cycled**	2.02 ± 0.15 (3)	170 ± 18 (3)	19.5 ± 1.5 (3)	56.3 ± 2.6 (3)	4.05 ± 0.21 (3)	0.034 ± 0.003 (2)	*170 ± 12 (3)*	5.30 ± 0.29 (3)	12.3 ± 0.6 (3)	1.78 ± 0.12 (3)	8.7 ± 0.6 (3)	2.43 ± 0.10 (3)
	Certificate	1.91 ± 0.01	169.2 ± 0.7	19	59	5.7	0.26	*200*	5.3	13.3	2	8.9	2.79
RGM-1	**Compiled**	151 ± 10 (33)	104 ± 4 (33)	22.3 ± 0.9 (33)	231 ± 9 (33)	8.91 ± 0.26 (33)	10.2 ± 0.3 (33)	*835 ± 19 (33)*	24.0 ± 0.8 (33)	48.0 ± 1.4 (33)	5.50 ± 0.18 (33)	20.2 ± 0.7 (33)	4.07 ± 0.15 (33)
	Certificate	150 ± 16	110 ± 20	25	220 ± 40	8.9 ± 1.2	9.6 ± 1.2	*810 ± 92*	24.0 ± 2.2	47 ± 8		19 ± 2	4.3 ± 0.6
	Reference[5]	152 ± 3	107.6 ± 1.0	22 ± 1	237 ± 6		10 ± 0.1	*822 ± 34*	22 ± 1.1	45 ± 2.2	5.3 ± 0.3	18.7 ± 0.8	3.82 ± 0.08
STM-1	**Cycled**	117 ± 5 (5)	717 ± 29 (5)	44.9 ± 2.3 (5)	1430 ± 100 (6)	269 ± 9 (4)[8]	1.58 ± 0.09 (3)	*599 ± 19 (5)*	160 ± 6 (5)	280 ± 8 (5)	27.7 ± 1.6 (5)	87 ± 5 (5)	13.0 ± 0.5 (5)
	Certificate	118 ± 12	700 ± 60	46 ± 10	1,210 ± 280	270 ± 24	1.54 ± 0.20	*560 ± 120*	150 ± 12	259 ± 36	19.0 ± 5.2	79 ± 14	13 ± 2
	Reference[5, 7]	114 ± 7.5	685 ± 6.2	42 ± 1.6	1318 ± 10.5		1.52 ± 0.07	*568 ± 1.7*	146 ± 2.8	252 ± 2.3	26 ± 1.0	79 ± 4.3	11.8 ± 0.5
SY-4	**Cycled**	57.8 ± 2.4 (3)	1,260 ± 70 (3)	126.2 ± 3.1 (3)	570 ± 50 (2)	14.6 ± 1.2 (3)	1.627 (1)	*348 ± 13 (3)*	62 ± 4 (3)	132 ± 7 (3)	16.1 ± 0.5 (3)	62.8 ± 2.6 (3)	13.7 ± 0.6 (3)
	Compiled	55 ± 4 (31)	1,190 ± 50 (31)	121 ± 5 (31)	510 ± 20 (31)	14.3 ± 0.4 (31)	1.64 ± 0.06 (31)	*342 ± 9 (31)*	60.9 ± 1.8 (31)	129 ± 4 (31)	15.8 ± 0.5 (31)	61.6 ± 2.0 (31)	13.5 ± 0.4 (31)
	Certificate	55.0 ± 1.5	1,191 ± 12	119 ± 2	517 ± 16	13 ± 1	1.5 ± 0.1	*340 ± 5*	58 ± 1	122 ± 2	15.0 ± 0.3	57 ± 1	12.7 ± 0.4
	Reference[5]	54.8 ± 0.5	1,248 ± 23.7	121 ± 3.9	512 ± 36.9		1.58 ± 0.03	*318 ± 3.8*	56.8 ± 0.7	120 ± 1.2	15 ± 0.2	59.8 ± 0.7	13 ± 0.3
In-House Reference Materials													
LKNIP-1	**Cycled**	13.1 ± 0.4 (5)	176 ± 5 (5)	22.7 ± 0.7 (5)	88 ± 6 (5)	4.70 ± 0.16 (5)	N.M.	*138.6 ± 3.0 (5)*	8.8 ± 0.3 (5)	19.6 ± 0.6 (5)	2.64 ± 0.05 (5)	12.09 ± 0.21 (5)	3.21 ± 0.05 (5)
MRB-29	**Cycled**	15.2 ± 1.8 (140)	316 ± 18 (140)	26.8 ± 1.5 (140)	179 ± 10 (140)	13.3 ± 0.7 (140)	0.25 ± 0.04 (45)	*291 ± 14 (140)*	22.7 ± 1.2 (140)	51.2 ± 2.5 (140)	6.74 ± 0.32 (140)	29.1 ± 1.3 (140)	6.39 ± 0.30 (140)
MRB-32	**Cycled**	1.79 ± 0.10 (5)	38.7 ± 1.6 (5)	6.27 ± 0.25 (5)	27 ± 4 (4)	1.410 ± 0.024 (5)	0.9 ± 0.4 (4)	*4.22 ± 0.30 (5)*	1.65 ± 0.19 (5)	4.5 ± 0.4 (5)	0.69 ± 0.05 (5)	3.37 ± 0.15 (5)	1.02 ± 0.04 (5)
NPD-1	**Cycled**	48 ± 4 (13)	173 ± 8 (13)	25.3 ± 1.1 (13)	116 ± 11 (13)	6.30 ± 0.29 (13)	1.09 ± 0.05 (6)	*273 ± 14 (13)*	16.9 ± 1.1 (13)	35.9 ± 1.8 (13)	4.48 ± 0.21 (13)	18.7 ± 0.7 (13)	4.38 ± 0.17 (13)

Table 54.1. continued

		Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
Procedural Blanks														
	Average	0.001	0.005	0.0006	0.004	0.0009	0.003	0.0004	0.004	0.0005	0.03	0.04	0.02	0.004
	±	0.0026	0.010	0.0015	0.007	0.0017	0.0054	0.0011	0.008	0.0013	0.037	0.08	0.045	0.011
	n	143	135	139	143	139	144	140	144	140	144	140	144	144
	LLoD[1]	0.0049	0.02	0.0029	0.015	0.0034	0.0111	0.0021	0.016	0.0024	0.085	0.16	0.088	0.021
Inter-Laboratory Reference Materials														
AGV-2	**Cycled**	1.57 ± 0.09 (5)	4.69 ± 0.24 (5)	0.64 ± 0.04 (5)	3.59 ± 0.28 (5)	0.70 ± 0.04 (5)	1.93 ± 0.16 (5)	0.270 ± 0.017 (5)	1.72 ± 0.14 (5)	0.258 ± 0.025 (5)	5.43 ± 0.29 (5)	0.90 ± 0.13 (5)	6.36 ± 0.18 (5)	1.97 ± 0.04 (5)
	Compiled	1.58 ± 0.07 (34)	4.65 ± 0.17 (34)	0.642 ± 0.020 (34)	3.55 ± 0.11 (34)	0.684 ± 0.017 (34)	1.90 ± 0.06 (34)	0.266 ± 0.008 (34)	1.71 ± 0.04 (34)	0.258 ± 0.009 (34)	5.42 ± 0.19 (34)	0.899 ± 0.022 (34)	6.34 ± 0.14 (34)	1.98 ± 0.05 (34)
	Certificate	1.54 ± 0.20	4.69 ± 0.52	0.64 ± 0.08	3.6 ± 0.4	0.71 ± 0.16	1.79 ± 0.22	0.26 ± 0.04	1.6 ± 0.4	0.25 ± 0.02	5.08 ± 0.40	0.89 ± 0.16	6.1 ± 1.2	1.88 ± 0.32
	Reference[4]	1.53 ± 0.01	4.52	0.641	3.47	0.653	1.81 ± 0.01	0.259	1.62 ± 0.01	0.247 ± 0.004				
BHVO-2	**Cycled**	2.14 ± 0.09 (10)	6.50 ± 0.28 (10)	0.97 ± 0.04 (10)	5.49 ± 0.25 (10)	1.02 ± 0.04 (10)	2.66 ± 0.08 (10)	0.347 ± 0.012 (10)	2.09 ± 0.08 (10)	0.290 ± 0.012 (10)	4.60 ± 0.24 (10)	1.17 ± 0.10 (9)	1.29 ± 0.14 (10)	0.45 ± 0.06 (10)
	Certificate		6.3 ± 0.4	0.90		1.04 ± 0.08			2.0 ± 0.4	0.28 ± 0.02	4.1 ± 0.6	1.40	1.20 ± 0.60	
	Reference[4]	2.07 ± 0.01	6.24 ± 0.02	0.936 ± 0.016	5.31 ± 0.02	0.972 ± 0.038	2.54 ± 0.01	0.341 ± 0.008	2 ± 0.01	0.274				
BIR-1	**Cycled**	0.54 ± 0.03 (10)	1.93 ± 0.11 (10)	0.372 ± 0.022 (10)	2.61 ± 0.17 (10)	0.59 ± 0.05 (10)	1.78 ± 0.16 (10)	0.261 ± 0.028 (10)	1.70 ± 0.21 (10)	0.255 ± 0.031 (10)	0.63 ± 0.06 (10)	0.08 ± 0.08 (10)	0.04 ± 0.03 (10)	0.013 ± 0.006 (10)
	Compiled	0.541 ± 0.025 (34)	1.96 ± 0.09 (34)	0.376 ± 0.015 (34)	2.63 ± 0.10 (34)	0.591 ± 0.022 (34)	1.79 ± 0.07 (34)	0.265 ± 0.009 (34)	1.72 ± 0.06 (34)	0.263 ± 0.009 (34)	0.66 ± 0.03 (34)	0.125 ± 0.007 (34)	0.044 ± 0.020 (34)	0.015 ± 0.005 (34)
	Certificate	0.55 ± 0.10	1.85 ± 0.80						1.7 ± 0.2	0.26	0.60 ± 0.16			
	Reference[5]	0.53 ± 0.01	1.91 ± 0.06	0.36 ± 0.01	2.55 ± 0.09	0.56 ± 0.02	1.71 ± 0.08	0.25 ± 0.01	1.64 ± 0.06	0.25 ± 0.01	0.6 ± 0.1		0.028 ± 0.001	0.009 ± 0.001
GSP-2	**Cycled**	2.33 ± 0.21 (6)	12.3 ± 1.9 (6)	1.30 ± 0.19 (6)	5.8 ± 0.6 (6)	0.98 ± 0.08 (6)	2.41 ± 0.15 (6)	0.300 ± 0.021 (6)	1.77 ± 0.13 (6)	0.238 ± 0.017 (6)	14.1 ± 1.3 (6)	0.90 ± 0.10 (4)	116.59 (1)[11]	2.58 ± 0.23 (6)
	Certificate	2.3 ± 0.2	12 ± 4		6.10	1.0 ± 0.2	2.20	0.29 ± 0.04	1.6 ± 0.4	0.23 ± 0.06	14 ± 2		105 ± 16	2.40 ± 0.38
	Reference[4]	2.27	12.2		5.74	1	2.26 ± 0.12	0.298	1.64 ± 0.02	0.223				
GSR-1	**Cycled**	0.85 ± 0.04 (26)	9.1 ± 0.5 (26)	1.62 ± 0.11 (26)	10.2 ± 0.8 (26)	2.14 ± 0.18 (26)	6.8 ± 0.6 (26)	1.11 ± 0.11 (26)	7.8 ± 0.7 (26)	1.18 ± 0.13 (26)	5.8 ± 0.4 (22)	6.8 ± 0.4 (26)	56.6 ± 2.6 (24)[12]	20.2 ± 1.1 (26)
	Certificate	0.85 ± 0.04	9.3 ± 0.4	1.65 ± 0.06	10.2 ± 0.2	2.05 ± 0.11	6.5 ± 0.2	1.06 ± 0.06	7.4 ± 0.2	1.15 ± 0.06	6.3 ± 0.5	7.2 ± 0.4	54.0 ± 1.3	18.8 ± 1.0
	Reference[6]	0.82 ± 0.03	8.64 ± 0.19	1.62 ± 0.06	10.1 ± 0.4	2.14 ± 0.06	6.49 ± 0.15	1.11 ± 0.04	7.68 ± 0.23	1.18 ± 0.04	5.84 ± 0.30	7.07 ± 0.3	56.4 ± 2.7	20.4 ± 1.1
GSR-2	**Cycled**	1.03 ± 0.11 (21)	2.57 ± 0.30 (21)	0.33 ± 0.03 (21)	1.73 ± 0.16 (21)	0.317 ± 0.031 (21)	0.85 ± 0.08 (21)	0.117 ± 0.011 (21)	0.75 ± 0.09 (21)	0.109 ± 0.011 (21)	2.50 ± 0.14 (21)	0.34 ± 0.10 (21)	2.61 ± 0.27 (21)	0.91 ± 0.04 (21)
	Compiled	1.05 ± 0.04 (33)	2.61 ± 0.10 (33)	0.336 ± 0.012 (33)	1.76 ± 0.06 (33)	0.322 ± 0.013 (33)	0.86 ± 0.03 (33)	0.119 ± 0.005 (33)	0.766 ± 0.027 (33)	0.112 ± 0.005 (33)	2.56 ± 0.11 (33)	0.410 ± 0.011 (33)	2.67 ± 0.08 (33)	0.910 ± 0.024 (33)
	Certificate	1.02 ± 0.03	2.7 ± 0.2	0.41 ± 0.03	1.80 ± 0.12	0.34 ± 0.20	0.85 ± 0.08	0.15	0.89 ± 0.07	0.12 ± 0.02	2.9 ± 0.3	0.46	2.60 ± 0.20	0.90 ± 0.09
	Reference[6]	1.04 ± 0.02	2.47 ± 0.04	0.35 ± 0.01	1.72 ± 0.04	0.31 ± 0.01	0.84 ± 0.03	0.12 ± 0.01	0.75 ± 0.01	0.11 ± 0.01	2.71 ± 0.08	0.37 ± 0.01	2.83 ± 0.02	0.90 ± 0.02
GSR-3	**Cycled**	3.35 ± 0.17 (15)	8.8 ± 0.5 (15)	1.15 ± 0.06 (15)	5.56 ± 0.24 (15)	0.90 ± 0.04 (15)	2.02 ± 0.10 (15)	0.235 ± 0.011 (15)	1.32 ± 0.08 (15)	0.162 ± 0.010 (15)	6.47 ± 0.28 (15)	4.13 ± 0.18 (15)	6.1 ± 0.3 (15)	1.48 ± 0.08 (15)
	Compiled	3.29 ± 0.11 (32)	8.63 ± 0.24 (32)	1.12 ± 0.04 (32)	5.49 ± 0.17 (32)	0.882 ± 0.029 (32)	1.99 ± 0.07 (32)	0.232 ± 0.009 (32)	1.30 ± 0.05 (32)	0.160 ± 0.006 (32)	6.36 ± 0.24 (32)	4.32 ± 0.11 (32)	6.03 ± 0.19 (32)	1.48 ± 0.05 (32)
	Certificate	3.20 ± 0.15	8.5 ± 0.4	1.2 ± 0.1	5.60 ± 0.15	0.88 ± 0.20	2.00 ± 0.14	0.28 ± 0.02	1.5 ± 0.2	0.19 ± 0.03	6.5 ± 0.4	4.3 ± 0.4	6.00 ± 0.50	1.4 ± 0.2
	Reference[6]	3.37 ± 0.11	8.56 ± 0.19	1.24 ± 0.04	5.88 ± 0.17	0.91 ± 0.05	2.07 ± 0.10	0.26 ± 0.01	1.30 ± 0.07	0.18 ± 0.01	6.82 ± 0.16	4.40 ± 0.14	6.26 ± 0.28	1.48 ± 0.06
NBS-688	**Cycled**	1.019 ± 0.029 (3)	3.077 ± 0.024 (3)	0.525 ± 0.007 (3)	3.40 ± 0.06 (3)	0.738 ± 0.012 (3)	2.213 ± 0.029 (3)	0.322 ± 0.009 (3)	2.13 ± 0.04 (3)	0.325 ± 0.009 (3)	1.51 ± 0.04 (3)	0.27 ± 0.07 (3)	0.34 ± 0.08 (3)	0.29 ± 0.06 (3)
	Certificate	1.07	3.2	0.448	3.3	0.75	2.09	0.3	2.09	0.34	1.6	0.31	0.33 ± 0.02	0.37
RGM-1	**Compiled**	0.63 ± 0.04 (33)	3.73 ± 0.15 (33)	0.609 ± 0.021 (33)	3.75 ± 0.12 (33)	0.786 ± 0.029 (33)	2.42 ± 0.09 (33)	0.380 ± 0.012 (33)	2.60 ± 0.07 (33)	0.407 ± 0.012 (33)	6.17 ± 0.21 (33)	0.947 ± 0.024 (33)	15.0 ± 0.4 (33)	5.86 ± 0.18 (33)
	Certificate	0.66 ± 0.16	3.7 ± 0.8		4.1 ± 0.2				2.6 ± 0.6	0.41 ± 0.06		0.95 ± 0.20	15.1 ± 2.6	5.8 ± 1
	Reference[5]	0.61 ± 0.04	3.7 ± 0.2	0.59 ± 0.04	3.6 ± 0.1	0.75 ± 0.05	2.29 ± 0.08	0.36 ± 0.02	2.53 ± 0.04	0.39 ± 0.02	6.4 ± 0.2		14 ± 1.6	5.5 ± 0.2
STM-1	**Cycled**	3.64 ± 0.14 (5)	9.4 ± 0.4 (5)	1.48 ± 0.07 (5)	8.4 ± 0.3 (5)	1.61 ± 0.07 (5)	4.67 ± 0.24 (5)	0.70 ± 0.03 (5)	4.60 ± 0.21 (5)	0.67 ± 0.03 (5)	29.7 ± 1.0 (5)	17.6 ± 0.4 (5)	31.5 ± 0.9 (5)	9.09 ± 0.25 (5)
	Certificate	3.6 ± 0.6	9.5 ± 1.6	1.6 ± 0.4	8.1 ± 1.0	1.9 ± 1.0	4.2 ± 0.8	0.70	4.4 ± 0.8	0.60 ± 0.22	28 ± 4	19 ± 24	31 ± 6	9.1 ± 0.2
	Reference[5, 7]	3.4 ± 0.1	9.2 ± 0.4	1.41 ± 0.09	7.9 ± 0.4	1.46 ± 0.07	4.2 ± 0.2	0.65 ± 0.04	4.2 ± 0.2	0.63 ± 0.03	30 ± 2.1	17.5	30.2 ± 0.6	8.6 ± 0.5
SY-4	**Cycled**	2.086 ± 0.031 (3)	15.2 ± 0.5 (3)	2.86 ± 0.06 (3)	19.9 ± 0.8 (3)	4.68 ± 0.17 (3)	15.46 ± 0.28 (3)	2.47 ± 0.08 (3)	15.9 ± 0.4 (3)	2.24 ± 0.10 (3)	10.4 ± 1.1 (2)	0.83 ± 0.18 (3)	1.28 ± 0.09 (3)	0.83 ± 0.21 (2)
	Compiled	2.05 ± 0.06 (31)	14.8 ± 0.5 (31)	2.78 ± 0.08 (31)	19.5 ± 0.7 (31)	4.61 ± 0.17 (31)	15.3 ± 0.5 (31)	2.42 ± 0.08 (31)	15.7 ± 0.5 (31)	2.22 ± 0.07 (31)	9.6 ± 0.4 (31)	0.845 ± 0.020 (31)	1.31 ± 0.05 (31)	0.863 ± 0.030 (31)
	Certificate	2.00 ± 0.04	14.0 ± 0.5	2.6 ± 0.1	18.2 ± 0.6	4.3 ± 0.1	14.2 ± 0.5	2.3 ± 0.1	14.8 ± 0.4	2.1 ± 0.1	10.6 ± 0.4	0.9 ± 0.1	1.4 ± 0.2	0.8 ± 0.1
	Reference[5]	2.14 ± 0.08	14.8 ± 0.3	2.94 ± 0.06	19.5 ± 0.3	4.45 ± 0.09	15.2 ± 0.3	2.35 ± 0.05	15.7 ± 0.4	2.23 ± 0.05	9.4 ± 0.7	0.786	1.3 ± 0.2	0.78 ± 0.09
In-House Reference Materials														
LKNIP-1	**Cycled**	1.13 ± 0.03 (5)	3.92 ± 0.07 (5)	0.658 ± 0.020 (5)	4.10 ± 0.08 (5)	0.850 ± 0.012 (5)	2.47 ± 0.07 (5)	0.351 ± 0.004 (5)	2.24 ± 0.04 (5)	0.331 ± 0.010 (5)	2.32 ± 0.10 (5)	0.283 ± 0.006 (5)	1.57 ± 0.06 (5)	0.457 ± 0.024 (5)
MRB-29	**Cycled**	1.95 ± 0.09 (140)	6.22 ± 0.30 (140)	0.93 ± 0.04 (140)	5.37 ± 0.24 (140)	1.05 ± 0.05 (140)	2.90 ± 0.14 (140)	0.40 ± 0.02 (140)	2.54 ± 0.13 (140)	0.37 ± 0.02 (140)	4.59 ± 0.23 (140)	0.81 ± 0.09 (138)	2.69 ± 0.18 (140)	0.66 ± 0.05 (140)
MRB-32	**Cycled**	0.284 ± 0.008 (5)	1.23 ± 0.04 (5)	0.204 ± 0.012 (5)	1.25 ± 0.05 (5)	0.252 ± 0.018 (5)	0.70 ± 0.04 (5)	0.100 ± 0.007 (5)	0.64 ± 0.06 (5)	0.094 ± 0.009 (5)	0.76 ± 0.09 (4)	0.17 ± 0.09 (4)	0.185 ± 0.025 (5)	0.058 ± 0.007 (5)
NPD-1	**Cycled**	1.31 ± 0.05 (13)	4.76 ± 0.25 (13)	0.77 ± 0.04 (13)	4.77 ± 0.21 (13)	0.98 ± 0.04 (13)	2.83 ± 0.15 (13)	0.409 ± 0.020 (13)	2.65 ± 0.14 (13)	0.398 ± 0.016 (13)	3.19 ± 0.19 (13)	0.49 ± 0.11 (12)	4.7 ± 0.3 (13)	1.54 ± 0.09 (13)

Table 54.2. Summary of trace element data obtained on the Elan 9000 ICP–MS using the IM-100 package (after closed-beaker digestion).

		Li	Be	Sc	Ti	V	Cr	Co	Ni	Cu	Zn	Ga
Procedural Blanks												
	Average	0.06	0.02	0.4	6	2	10	0.03	0.8	0.5	3	0.017
	2SD	0.093	0.037	0.46	20	8.3	14	0.073	1.7	1.4	5.3	0.028
	n	54	53	54	54	54	54	54	54	51	52	54
	LLoD[1]	0.153	0.057	0.86	26	10.3	24	0.103	2.5	1.9	8.3	0.045
Inter-Laboratory Reference Materials												
AGV-2	**Cycled**	14.9 (1)[2]	2.52 (1)	12.9 (1)	5,264 (1)	122 (1)	23.3 (1)	15.5 (1)	19.1 (1)	52.2 (1)	78.4 (1)	20.2 (1)
	Compiled	11.7 ± 0.7[3] (12)	2.33 ± 0.25 (12)	13.2 ± 0.6 (12)	5,740 ± 1,040 (12)	123 ± 7 (12)	17.6 ± 1.0 (12)	16.0 ± 0.6 (12)	20.0 ± 1.3 (12)	53 ± 5 (12)	85 ± 11 (12)	20.3 ± 0.7 (12)
	Certificate	11	2.3 ± 0.8	13 ± 2	6,300 ± 2,600	120 ± 10	17 ± 4	16 ± 2	19 ± 6	53 ± 8	86 ± 16	20 ± 2
	Reference[4]											
BHVO-2	**Cycled**	5.1 ± 0.5 (6)	1.15 ± 0.09 (6)	33.0 ± 2.5 (6)	14,580 ± 1,540 (3)[9]	331 ± 26 (6)	315 ± 23 (6)	47 ± 4 (6)	128 ± 8 (6)	134 ± 11 (6)	112 ± 13 (6)	21.7 ± 1.5 (6)
	Certificate	5		32 ± 2	16,300 ± 400	317 ± 22	280 ± 38	45 ± 6	119 ± 14	127 ± 14	103 ± 12	21.7 ± 1.8
	Reference[4]											
BIR-1	**Cycled**	3.8 ± 0.8 (3)	0.14 ± 0.08 (3)	46 ± 7 (3)	5,840 ± 1,350 (3)	342 ± 45 (3)	417 ± 45 (3)	55 ± 6 (3)	184 ± 26 (3)	126 ± 18 (3)	73 ± 18 (3)	15.8 ± 2.0 (3)
	Compiled	3.8 ± 0.6 (14)	0.14 ± 0.08 (14)	45.4 ± 2.5 (14)	5,350 ± 1,060 (14)	334 ± 18 (14)	405 ± 21 (14)	53.3 ± 2.4 (14)	187 ± 9 (14)	121 ± 7 (14)	70 ± 9 (14)	15.4 ± 0.4 (14)
	Certificate	3.6 ± 0.4	0.58	44 ± 2	5,755 ± 120	310 ± 22	370 ± 16	52 ± 4	170 ± 12	125 ± 8	70 ± 18	16
	Reference[5, 6]											
GSP-2	**Cycled**	40.9 ± 1.0 (2)	1.59 ± 0.16 (2)	7.0 ± 0.5 (2)	4,210 ± 510 (2)	55 ± 4 (2)	26.9 ± 1.6 (2)	7.5 ± 0.7 (2)	17.6 ± 1.7 (2)	45.4 ± 2.0 (2)	105 ± 15 (2)	24.6 ± 1.8 (2)
	Certificate	36 ± 2	1.5 ± 0.4	6.3 ± 1.4	4,000 ± 200	52 ± 8	20 ± 12	7.3 ± 1.6	17 ± 4	43 ± 8	120 ± 20	22 ± 4
	Reference[4]											
GSR-1	**Cycled**	148 ± 11 (5)	13.8 ± 2.0 (6)	6.5 ± 1.0 (6)	1,531 ± 225 (6)	28 ± 11 (6)	13 ± 5 (6)	2.93 ± 0.26 (6)	1.47 ± 0.19 (6)	4.0 ± 3.1 (6)	26 ± 4 (6)	19.4 ± 1.5 (6)
	Certificate	131 ± 3	12.4 ± 0.7	6.1 ± 0.2	1,739 ± 30	24 ± 1	5.0	3.4 ± 0.2	2.30 ± 0.30	3.2 ± 0.4	28 ± 1	19 ± 1
	Reference[7]	145 ± 8		6.21 ± 0.10		20.3 ± 1.4	2.19 ± 0.31	3.06 ± 0.18	1.35 ± 0.14	3.53 ± 0.22	27 ± 1	20.6 ± 0.1
GSR-2	**Cycled**	21 ± 3 (8)	1.13 ± 0.16 (8)	9.1 ± 0.8 (8)	2,730 ± 430 (8)	100 ± 8 (8)	46 ± 9 (8)	13.2 ± 1.1 (8)	20 ± 6 (8)	55.7 ± 2.8 (8)	63 ± 7 (8)	18.1 ± 1.7 (8)
	Compiled	21.1 ± 1.7 (14)	1.10 ± 0.13 (13)	9.6 ± 0.5 (13)	2,760 ± 550 (14)	98 ± 9 (13)	32.7 ± 1.9 (13)	12.7 ± 0.7 (14)	18.4 ± 1.3 (14)	56 ± 4 (14)	64 ± 8 (14)	17.9 ± 0.8 (14)
	Certificate	18.3 ± 0.5	1.1 ± 0.1	9.5 ± 0.4	3,117 ± 40	95.5 ± 1.6	32.4 ± 1.3	13.2 ± 0.4	17 ± 1	55.4 ± 1.1	71 ± 2	18.1 ± 0.9
	Reference[7]	22.6 ± 0.3		8.18 ± 0.21		85.3 ± 6.0	31.3 ± 0.2	11.5 ± 0.3	17.4 ± 0.2	53.9 ± 0.5	62.2 ± 0.5	18.4 ± 0.3
GSR-3	**Cycled**	10.7 ± 0.8 (4)	2.8 ± 0.4 (4)	15.3 ± 1.1 (4)	12,750 ± 1,320 (2)[10]	180 ± 13 (4)	163 ± 13 (4)	50 ± 4 (4)	158 ± 15 (4)	54.0 ± 3.1 (4)	148 ± 26 (4)	24.5 ± 1.8 (4)
	Compiled	10.3 ± 0.8 (14)	2.66 ± 0.25 (14)	14.8 ± 0.8 (14)	11,940 ± 1,000 (5)[11]	171 ± 7 (14)	144 ± 5 (14)	47.3 ± 1.8 (14)	147 ± 5 (14)	52 ± 4 (14)	140 ± 13 (14)	23.4 ± 0.8 (14)
	Certificate	9.5 ± 0.5	2.5 ± 0.2	15.2 ± 0.7	14,148 ± 200	167 ± 5	134 ± 4	46.5 ± 1.3	140 ± 3	48.6 ± 1.1	150 ± 4	24.8 ± 0.6
	Reference[7]	10.9 ± 0.2		15.3 ± 0.5		158 ± 7	150 ± 6	47.6 ± 2.5	148 ± 7	52.2 ± 2.4	146 ± 2	25.6 ± 0.9
RGM-1	**Cycled**	51.5 ± 2.4 (2)	2.19 ± 0.06 (2)	4.3 ± 0.4 (2)	1,186 ± 40 (2)	15.4 ± 1.0 (2)	15 ± 12 (2)	1.88 ± 0.27 (2)	5 ± 7 (2)	10.6 ± 0.3 (2)	31.7 ± 1.7 (2)	15.1 ± 1.1 (2)
	Compiled	66 ± 4 (13)	2.47 ± 0.19 (14)	5.2 ± 0.5 (14)	1,434 ± 274 (14)	15 ± 7 (14)	4.8 ± 1.1 (14)	1.99 ± 0.08 (14)	2.5 ± 0.6 (14)	12.8 ± 2.0 (14)	33 ± 7 (14)	15.8 ± 0.6 (14)
	Certificate	57 ± 16	2.4 ± 0.4	4.4 ± 0.6	1,601 ± 240	13 ± 4	3.7	2.0 ± 0.4	4.4 ± 1.8	11.6 ± 2.8	32	15 ± 4
	Reference[5]											
STM-1	**Cycled**	38 ± 6 (4)	9.7 ± 1.1 (4)	1.34 ± 0.28 (4)	729 ± 228 (4)	5 ± 5 (4)	12 ± 9 (4)	0.80 ± 0.05 (4)	2.9 ± 1.6 (4)	3.5 ± 0.4 (4)	203 ± 10 (4)	34.8 ± 1.8 (4)
	Certificate	32	9.6 ± 1.2	0.61 ± 0.14	809 ± 240	8.7	4.3	0.9	3	4.6	235 ± 44	35 ± 10
	Reference[5, 8]											
SY-4	**Cycled**	45 ± 7 (7)	3.2 ± 0.4 (7)	1.37 ± 0.28 (7)	1,639 ± 232 (7)	12 ± 7 (7)	21 ± 11 (7)	2.7 ± 0.4 (7)	9.0 ± 2.4 (7)	4.5 ± 0.8 (7)	85 ± 6 (7)	37 ± 4 (7)
	Compiled	41 ± 4 (14)	3.07 ± 0.22 (14)	2.0 ± 0.4 (14)	1,576 ± 271 (14)	12 ± 9 (14)	10.5 ± 0.8 (14)	2.66 ± 0.21 (14)	8.2 ± 0.5 (14)	6.1 ± 1.7 (14)	83 ± 9 (14)	35.1 ± 0.9 (14)
	Certificate	37 ± 2	2.6 ± 0.1	1.1 ± 0.1	1,721	8.0 ± 1.6	12 ± 1	2.8 ± 0.2	9 ± 1	7 ± 1	93 ± 2	35 ± 1
	Reference[4]											
In-House Reference Materials												
MRB-29	**Cycled**	12.2 ± 1.8 (55)	1.14 ± 0.19 (55)	33.2 ± 3.1 (55)	10,018 ± 991 (34)[12]	317 ± 28 (54)[13]	291 ± 30 (55)	51.5 ± 4.3 (55)	115.1 ± 9.3 (55)	149 ± 26 (55)	106 ± 11 (55)	19.7 ± 1.7 (55)
MRB-32	**Cycled**	5.8 ± 1.2 (3)	0.334 ± 0.085 (3)	17.15 ± 0.85 (3)	2,435 ± 708 (3)	127.2 ± 4.3 (3)	3,660 ± 1,140 (3)	158.6 ± 4.5 (3)	2,861 ± 873 (3)	2,564 ± 645 (3)	123.8 ± 6.7 (3)	6.019 ± 0.076 (3)
NPD-1	**Cycled**	23.5 ± 2.6 (6)	1.089 ± 0.092 (6)	36.9 ± 1.5 (6)	6,660 ± 1,240 (6)	283 ± 12 (6)	135.4 ± 5.1 (6)	47.7 ± 3.2 (6)	69.9 ± 6.6 (6)	143 ± 11 (6)	189 ± 22 (6)	19.4 ± 1.3 (6)

Table 54.2. continued

		Rb	Sr	Y	Zr	Nb	Mo	Cd	Sn	Sb	Cs^{16}	Ba
Procedural Blanks												
	Average	0.04	0.2	0.02	0.9	0.01	0.09	0.002	0.05	0.012	0.0023	0.3
	2SD	0.11	0.55	0.054	2.4	0.037	0.22	0.0051	0.058	0.023	0.0024	0.44
	n	52	54	54	51	52	54	53	54	46	28	53
	LLoD^1	0.15	0.75	0.074	3.3	0.047	0.31	0.0071	0.108	0.035	0.0047	0.74
Inter-Laboratory Reference Materials												
AGV-2	**Cycled**	40.3 (1)	375 (1)	18.2 (1)	232 (1)	13.6 (1)	2.22 (1)	0.0880 (1)	1.87 (1)	0.497 (1)	1.08 (1)	1,131 (1)
	Compiled	69.6 ± 2.6 (12)	665 ± 23 (12)	20.6 ± 0.7 (12)	236 ± 6 (12)	13.57 ± 0.29 (12)	2.32 ± 0.11 (12)	0.083 ± 0.013 (12)	1.93 ± 0.19 (12)	0.453 ± 0.018 (12)	1.25 ± 0.04 (12)	1,160 ± 22 (12)
	Certificate	68.6 ± 4.6	658 ± 34	20 ± 2	230 ± 8	15 ± 2			2.30 ± 0.80	0.6	1.16 ± 0.16	1,140 ± 64
	Reference^4	66.3 ± 0.4	661 ± 1.3									1,130
BHVO-2	**Cycled**	9.8 ± 0.8 (6)	409 ± 30 (6)	28.2 ± 2.2 (6)	177 ± 13 (6)	18.2 ± 1.4 (6)	5.2 ± 2.5 (6)	0.083 ± 0.010 (6)	1.78 ± 0.13 (6)	0.13 ± 0.06 (6)	0.112 ± 0.004 (3)	137 ± 12 (6)
	Certificate	9.8 ± 2.0	389 ± 46	26 ± 4	172 ± 22	18 ± 4			1.9			130 ± 26
	Reference^4	9.08 ± 0.06	396 ± 0.8									131
BIR-1	**Cycled**	0.30 ± 0.04 (3)	114 ± 18 (3)	17.2 ± 2.5 (3)	16.2 ± 1.2 (3)	0.57 ± 0.09 (3)	0.14 ± 0.11 (3)	0.048 ± 0.003 (3)	0.75 ± 0.14 (3)	0.52 ± 0.13 (3)	0.008 (2)	7.0 ± 1.1 (3)
	Compiled	0.34 ± 0.14 (14)	110 ± 4 (14)	16.7 ± 0.5 (14)	17.5 ± 0.6 (14)	0.535 ± 0.026 (14)	0.20 ± 0.06 (14)	0.047 ± 0.012 (14)	0.80 ± 0.07 (14)	0.501 ± 0.021 (14)	0.014 ± 0.007 (14)	7.5 ± 2.0 (14)
	Certificate		108 ± 4	16 ± 2	18 ± 2	0.6				0.58		7
	Reference^5	0.36 ± 0.05	110 ± 5	14.9 ± 0.5	15.4 ± 0.8		0.055 ± 0.018				0.0009	6.4 ± 0.7
GSP-2	**Cycled**	260 ± 21 (2)	247 ± 21 (2)	29 ± 4 (2)	518 ± 67 (2)	26.8 ± 1.9 (2)	2.50 ± 0.23 (2)	0.130 ± 0.011 (2)	6.5 ± 0.6 (2)	0.361 ± 0.017 (2)	1.31 ± 0.10 (2)	1,389 ± 200 (2)
	Certificate	245 ± 14	240 ± 20	28 ± 4	550 ± 60	27 ± 4	2.1 ± 1.2				1.2 ± 0.2	1,340 ± 88
	Reference^4	242 ± 2	238 ± 1									1,340 ± 10.7
GSR-1	**Cycled**	495 ± 48 (6)	111 ± 9 (6)	74 ± 6 (6)	164 ± 20 (6)	43 ± 5 (6)	4.2 ± 1.0 (6)	0.043 ± 0.009 (6)	11.6 ± 1.6 (6)	0.281 ± 0.028 (6)	38.0 (1)	345 ± 51 (6)
	Certificate	466 ± 10	106 ± 3	62 ± 2	167 ± 5	40.0 ± 1.4	3.5 ± 0.1	0.032	12.5 ± 1.0	0.21 ± 0.03	38.4 ± 0.8	343 ± 13
	Reference^6	453 ± 15.0	112 ± 2	67.8 ± 1.7	152 ± 8	44.2 ± 0.9	4.13 ± 0.30				38.8 ± 0.7	315 ± 9
GSR-2	**Cycled**	40 ± 3 (8)	828 ± 79 (8)	9.4 ± 0.7 (8)	95 ± 7 (8)	5.4 ± 1.2 (8)	1.0 ± 1.7 (8)	0.040 ± 0.004 (8)	0.67 ± 0.04 (8)	0.17 ± 0.07 (8)	1.834 ± 0.013 (2)	1,040 ± 81 (8)
	Compiled	38.9 ± 1.5 (14)	816 ± 30 (14)	9.4 ± 0.3 (14)	94 ± 3 (14)	5.40 ± 0.22 (14)	0.78 ± 0.10 (13)	0.044 ± 0.008 (13)	0.97 ± 0.09 (13)	0.183 ± 0.012 (13)	1.84 ± 0.05 (14)	1,031 ± 20 (14)
	Certificate	37.6 ± 1.7	790 ± 16	9.30 ± 0.50	99 ± 5	6.8 ± 0.7	0.54 ± 0.05	0.061 ± 0.008	0.79 ± 0.11	0.12 ± 0.02	2.3 ± 0.4	1,020 ± 21
	Reference^6	33.0 ± 1.2	785 ± 15	8.71 ± 0.06	93 ± 1	5.46 ± 0.05	0.78 ± 0.07				1.63 ± 0.03	990 ± 8.0
GSR-3	**Cycled**	40 ± 4 (4)	1,177 ± 101 (4)	25.1 ± 2.3 (4)	295 ± 28 (4)	75 ± 7 (4)	3.5 ± 0.5 (4)	0.101 ± 0.013 (4)	2.1 ± 0.3 (4)	0.11 ± 0.10 (4)	0.474 (1)	566 ± 65 (4)
	Compiled	38.7 ± 1.0 (14)	1,137 ± 28 (14)	24.1 ± 0.5 (14)	284 ± 6 (14)	72.5 ± 1.4 (14)	3.43 ± 0.12 (14)	0.092 ± 0.010 (14)	2.1 ± 0.3 (14)	0.080 ± 0.011 (14)	0.468 ± 0.017 (14)	538 ± 12 (14)
	Certificate	37 ± 2	1,100 ± 30	22 ± 1	277 ± 10	68 ± 4	2.6 ± 0.1	0.067 ± 0.010	2.0 ± 0.3	0.083 ± 0.021	1.2	526 ± 12
	Reference^6	39.9 ± 0.5	1,155 ± 32	23.9 ± 1.1	275 ± 11	75.8 ± 3.2	3.1 ± 0.2				0.45 ± 0.02	541 ± 12
RGM-1	**Cycled**	144 ± 11 (2)	100 ± 7 (2)	22.8 ± 1.3 (2)	210 ± 12 (2)	8.2 ± 0.5 (2)	3.0 ± 0.9 (2)	0.068 ± 0.004 (2)	3.80 ± 0.16 (2)	1.15 ± 0.04 (2)	10.098 ± 0.007 (2)	802 ± 25 (2)
	Compiled	151 ± 5 (14)	104 ± 3 (14)	24.1 ± 0.7 (14)	225 ± 6 (14)	8.64 ± 0.23 (14)	2.88 ± 0.08 (14)	0.070 ± 0.013 (14)	32 ± 3 (14)	1.26 ± 0.14 (9)	10.62 ± 0.27 (14)	843 ± 17 (14)
	Certificate	150 ± 16	110 ± 20	25	220 ± 40	8.9 ± 1.2	2.3 ± 1		4.1 ± 0.8	1.26 ± 0.20	9.6 ± 1.2	810 ± 92
	Reference^5	152 ± 3	107.6 ± 1.0	22 ± 1	237 ± 6						10.0 ± 0.1	822 ± 34
STM-1	**Cycled**	115 ± 4 (4)	696 ± 46 (4)	46.7 ± 2.9 (4)	1,363 (1)^{14}	251 ± 11 (2)^{15}	5.9 ± 0.3 (4)	0.38 ± 0.05 (4)	7.3 ± 0.8 (4)	1.57 ± 0.13 (4)	1.62 ± 0.11 (3)	592 ± 31 (4)
	Certificate	118 ± 12	700 ± 60	46 ± 10	1,210 ± 240	270 ± 24	5.2	0.27	6.8	1.7 ± 0.4	1.54 ± 0.20	560 ± 120
	Reference^{5,7}	114 ± 8	685 ± 6	42 ± 2	1318 ± 11						1.52 ± 0.07	568 ± 1.7
SY-4	**Cycled**	58 ± 6 (7)	1,250 ± 157 (7)	135 ± 25 (7)	558 ± 81 (6)	14.5 ± 1.7 (7)	0.30 ± 0.05 (7)	0.15 ± 0.05 (7)	7.8 ± 0.9 (7)	0.022 ± 0.013 (5)	1.67 ± 0.09 (2)	353 ± 49 (7)
	Compiled	55.8 ± 1.1 (14)	1,191 ± 28 (14)	131 ± 3 (14)	495 ± 13 (14)	13.8 ± 0.4 (14)	0.36 ± 0.04 (14)	0.128 ± 0.029 (14)	7.7 ± 2.0 (14)	0.032 ± 0.008 (14)	1.71 ± 0.04 (14)	344 ± 7 (14)
	Certificate	55.0 ± 1.5	1,191 ± 12	119 ± 2	517 ± 16	13 ± 1	0.2 - 3	0.1 - 2	7.1 ± 0.6	0.01 - 0.3	1.5 ± 0.1	340 ± 5
	Reference^5	54.8 ± 0.5	1,248 ± 24	121 ± 4	512 ± 37					0.011	1.58 ± 0.03	318 ± 3.8
In-House Reference Materials												
MRB-29	**Cycled**	15.3 ± 1.4 (55)	320 ± 27 (55)	29.4 ± 2.5 (55)	176 ± 15 (55)	12.9 ± 2.3 (55)	1.01 ± 0.86 (55)	0.083 ± 0.019 (55)	2.19 ± 0.39 (55)	0.075 ± 0.084 (55)	0.266 ± 0.029 (24)	298 ± 26 (55)
MRB-32	**Cycled**	1.634 ± 0.056 (3)	38.2 ± 1.4 (3)	6.789 ± 0.015 (3)	25.5 ± 1.3 (3)	1.342 ± 0.055 (3)	0.33 ± 0.18 (3)	0.58 ± 0.14 (3)	1.80 ± 0.86 (3)	1.632 ± 0.041 (3)	0.7745 ± 0.0071 (2)	4.21 ± 0.19 (3)
NPD-1	**Cycled**	51.4 ± 3.3 (6)	183 ± 12 (6)	28.9 ± 1.9 (6)	118.3 ± 10.0 (6)	6.48 ± 0.58 (6)	1.4 ± 1.2 (6)	0.201 ± 0.036 (6)	2.19 ± 0.34 (6)	0.52 ± 0.14 (6)	1.1810 ± 0.0028 (2)	290 ± 21 (6)

Table 54.2. continued

		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er
Procedural Blanks												
	Average	0.017	0.03	0.004	0.02	0.004	0.0013	0.005	0.0008	0.005	0.0007	0.003
	2SD	0.031	0.05	0.0074	0.044	0.0069	0.0027	0.009	0.0019	0.011	0.0019	0.006
	n	52	51	51	53	54	53	54	54	54	54	54
	LLoD[1]	0.048	0.08	0.0114	0.064	0.0109	0.004	0.014	0.0027	0.016	0.0026	0.009
Inter-Laboratory Reference Materials												
AGV-2	**Cycled**	31.2 (1)	59.0 (1)	6.99 (1)	27.2 (1)	4.82 (1)	1.38 (1)	4.08 (1)	0.582 (1)	3.08 (1)	0.604 (1)	1.56 (1)
	Compiled	37.8 ± 0.8 (12)	69.2 ± 1.6 (12)	8.08 ± 0.18 (12)	31.2 ± 0.5 (12)	5.60 ± 0.11 (12)	1.586 ± 0.029 (12)	4.63 ± 0.14 (12)	0.659 ± 0.012 (12)	3.46 ± 0.08 (12)	0.671 ± 0.019 (12)	1.73 ± 0.04 (12)
	Certificate	38 ± 2	68 ± 6	8.3 ± 1.2	30 ± 4	5.7 ± 0.6	1.54 ± 0.20	4.69 ± 0.52	0.64 ± 0.08	3.6 ± 0.4	0.71 ± 0.16	1.79 ± 0.22
	Reference[4]	37.9 ± 0.4	68.6 ± 0.5	7.68	30.5 ± 0.1	5.49 ± 0.02	1.53 ± 0.01	4.52	0.641	3.47	0.653	1.81 ± 0.01
BHVO-2	**Cycled**	15.8 ± 1.3 (6)	39 ± 4 (6)	5.5 ± 0.4 (6)	25.8 ± 2.1 (6)	6.4 ± 0.5 (6)	2.08 ± 0.17 (6)	6.3 ± 0.4 (6)	0.96 ± 0.09 (6)	5.4 ± 0.5 (6)	1.02 ± 0.11 (6)	2.48 ± 0.23 (6)
	Certificate	15 ± 2	38 ± 4		25.0 ± 3.6	6.2 ± 0.8		6.3 ± 0.4	0.9		1.04 ± 0.08	
	Reference[4]	15.2 ± 0.1	37.5 ± 0.1	5.29 ± 0.05	24.5	6.07 ± 0.01	2.07 ± 0.01	6.24 ± 0.02	0.936 ± 0.016	5.31 ± 0.02	0.972 ± 0.038	2.54 ± 0.01
BIR-1	**Cycled**	0.67 ± 0.11 (3)	2.0 ± 0.3 (3)	0.40 ± 0.08 (3)	2.6 ± 0.6 (3)	1.17 ± 0.17 (3)	0.54 ± 0.07 (3)	1.89 ± 0.23 (3)	0.37 ± 0.04 (3)	2.64 ± 0.31 (3)	0.61 ± 0.08 (3)	1.72 ± 0.20 (3)
	Compiled	0.67 ± 0.04 (14)	1.93 ± 0.06 (14)	0.385 ± 0.015 (14)	2.48 ± 0.11 (14)	1.12 ± 0.04 (14)	0.511 ± 0.016 (14)	1.75 ± 0.07 (14)	0.354 ± 0.012 (14)	2.59 ± 0.08 (14)	0.585 ± 0.019 (14)	1.65 ± 0.04 (14)
	Certificate	0.62 ± 0.14	1.95 ± 0.80		2.5 ± 1.4	1.1	0.55 ± 0.10	1.85 ± 0.80		4 ± 1		
	Reference[5]	0.62	1.89 ± 0.05	0.39 ± 0.01	2.35 ± 0.1	1.08 ± 0.05	0.53 ± 0.01	1.91 ± 0.06	0.36 ± 0.01	2.55 ± 0.09	0.56 ± 0.02	1.71 ± 0.08
GSP-2	**Cycled**	190 ± 26 (2)	447 ± 46 (2)	57 ± 8 (2)	216 ± 29 (2)	27 ± 4 (2)	2.33 ± 0.23 (2)	14.4 ± 1.6 (2)	1.59 ± 0.20 (2)	5.9 ± 0.7 (2)	0.99 ± 0.10 (2)	2.26 ± 0.22 (2)
	Certificate	180 ± 24	410 ± 60	51 ± 10	200 ± 24	27 ± 2	2.3 ± 0.2	12 ± 4		6.1	1.0 ± 0.2	2.2
	Reference[4]	186 ± 0.6	445 ± 1.3	50.7	207	26.2 ± 0.1	2.27	12.2		5.74	1	2.26 ± 0.12
GSR-1	**Cycled**	55 ± 8 (6)	114 ± 17 (6)	13.0 ± 1.9 (6)	47 ± 7 (6)	10.2 ± 1.4 (6)	0.85 ± 0.12 (6)	9.1 ± 1.2 (6)	1.65 ± 0.21 (6)	10.3 ± 1.4 (6)	2.20 ± 0.30 (6)	6.5 ± 0.8 (6)
	Certificate	54 ± 2	108 ± 4	12.7 ± 0.5	47 ± 2	9.7 ± 0.5	0.85 ± 0.04	9.3 ± 0.4	1.65 ± 0.06	10.2 ± 0.2	2.05 ± 0.11	6.5 ± 0.2
	Reference[6]	53.9 ± 1.2	112 ± 3	12.8 ± 0.3	44.3 ± 1.0	9.69 ± 0.08	0.82 ± 0.03	8.64 ± 0.19	1.62 ± 0.06	10.1 ± 0.4	2.14 ± 0.06	6.49 ± 0.15
GSR-2	**Cycled**	20.9 ± 1.4 (8)	40.1 ± 2.6 (8)	4.62 ± 0.30 (8)	18.4 ± 1.4 (8)	3.32 ± 0.26 (8)	1.06 ± 0.09 (8)	2.62 ± 0.16 (8)	0.346 ± 0.030 (8)	1.72 ± 0.12 (8)	0.317 ± 0.025 (8)	0.80 ± 0.05 (8)
	Compiled	21.4 ± 0.5 (13)	40.9 ± 0.7 (13)	4.72 ± 0.17 (14)	18.5 ± 0.3 (13)	3.35 ± 0.06 (13)	1.07 ± 0.04 (13)	2.62 ± 0.06 (13)	0.350 ± 0.013 (14)	1.74 ± 0.05 (13)	0.319 ± 0.008 (13)	0.798 ± 0.018 (13)
	Certificate	21.8 ± 1.0	40 ± 2	4.9 ± 0.2	19 ± 1	3.4 ± 0.1	1.02 ± 0.03	2.7 ± 0.2	0.41 ± 0.03	1.80 ± 0.12	0.34 ± 0.20	0.85 ± 0.08
	Reference[6]	20.6 ± 0.3	40.3 ± 0.7	4.65 ± 0.05	17.5 ± 0.1	3.11 ± 0.10	1.04 ± 0.02	2.47	0.35 ± 0.01	1.72 ± 0.04	0.31 ± 0.01	0.84 ± 0.03
GSR-3	**Cycled**	57 ± 6 (4)	110 ± 11 (4)	13.0 ± 1.3 (4)	54 ± 5 (4)	10.6 ± 1.0 (4)	3.3 ± 0.4 (4)	9.1 ± 0.8 (4)	1.21 ± 0.12 (4)	5.6 ± 0.6 (4)	0.91 ± 0.08 (4)	1.90 ± 0.14 (4)
	Compiled	54.8 ± 0.9 (14)	105.0 ± 1.9 (14)	12.34 ± 0.17 (14)	50.9 ± 1.0 (14)	10.11 ± 0.23 (14)	3.13 ± 0.07 (14)	8.49 ± 0.25 (14)	1.138 ± 0.022 (14)	5.37 ± 0.13 (14)	0.871 ± 0.023 (14)	1.82 ± 0.06 (14)
	Certificate	56 ± 2	105 ± 5	13.2 ± 0.8	54 ± 2	10.2 ± 0.3	3.20 ± 0.15	8.5 ± 0.4	1.2 ± 0.1	5.60 ± 0.15	0.88 ± 0.20	2.00 ± 0.14
	Reference[6]	58.9 ± 2.1	113 ± 4	13.4 ± 0.5	52.5 ± 1.8	10.4 ± 0.4	3.37 ± 0.11	8.56 ± 0.19	1.24 ± 0.04	5.88 ± 0.17	0.91 ± 0.05	2.07 ± 0.10
RGM-1	**Cycled**	22.0 ± 1.2 (2)	43.8 ± 1.8 (2)	5.06 ± 0.21 (2)	18.7 ± 0.7 (2)	3.85 ± 0.13 (2)	0.621 ± 0.025 (2)	3.52 ± 0.16 (2)	0.572 ± 0.021 (2)	3.49 ± 0.04 (2)	0.744 ± 0.021 (2)	2.12 ± 0.11 (2)
	Compiled	23.2 ± 0.5 (14)	46.2 ± 1.0 (14)	5.25 ± 0.11 (14)	19.8 ± 0.5 (14)	4.01 ± 0.09 (14)	0.658 ± 0.027 (14)	3.62 ± 0.10 (14)	0.602 ± 0.016 (14)	3.66 ± 0.10 (14)	0.774 ± 0.019 (14)	2.22 ± 0.05 (14)
	Certificate	24.0 ± 2.2	47 ± 8		19 ± 2	4.3 ± 0.6	0.66 ± 0.16	3.7 ± 0.8		4.1 ± 0.2		
	Reference[5]	22 ± 1.1	45 ± 2.2	5.3 ± 0.3	18.7 ± 0.8	3.82 ± 0.08	0.61 ± 0.04	3.7 ± 0.2	0.59 ± 0.04	3.6 ± 0.1	0.75 ± 0.05	2.29 ± 0.08
STM-1	**Cycled**	148 ± 17 (4)	259 ± 17 (4)	25.5 ± 2.0 (4)	82 ± 6 (4)	12.4 ± 1.0 (4)	3.37 ± 0.22 (4)	9.5 ± 0.7 (4)	1.50 ± 0.10 (4)	8.06 ± 0.18 (4)	1.55 ± 0.07 (4)	4.16 ± 0.13 (4)
	Certificate	150 ± 12	259 ± 36	19.0 ± 5.2	79 ± 14	13 ± 2	3.6 ± 0.6	9.5 ± 1.6	1.6 ± 0.4	8.1 ± 1.0	1.9 ± 1.0	4.2 ± 0.8
	Reference[5, 7]	146 ± 2.8	252 ± 2.3	26 ± 1.0	79 ± 4.1	11.8 ± 0.5	3.4 ± 0.1	9.2 ± 0.4	1.41 ± 0.09	7.9 ± 0.4	1.46 ± 0.07	4.2 ± 0.2
SY-4	**Cycled**	60 ± 9 (7)	128 ± 20 (7)	15.5 ± 2.5 (7)	61 ± 10 (7)	13.5 ± 2.2 (7)	2.0 ± 0.3 (7)	14.4 ± 2.5 (7)	2.7 ± 0.5 (7)	19 ± 4 (7)	4.6 ± 0.8 (7)	14.3 ± 2.5 (7)
	Compiled	58.8 ± 1.1 (14)	124.4 ± 2.4 (14)	15.14 ± 0.28 (14)	60.0 ± 1.1 (14)	13.2 ± 0.3 (14)	1.95 ± 0.03 (14)	14.1 ± 0.3 (14)	2.68 ± 0.06 (14)	19.0 ± 0.5 (14)	4.52 ± 0.13 (14)	14.0 ± 0.3 (14)
	Certificate	58 ± 1	122 ± 2	15.0 ± 0.3	57 ± 1	12.7 ± 0.4	2.00 ± 0.04	14.0 ± 0.5	2.6 ± 0.1	18.2 ± 0.6	4.3 ± 0.1	14.2 ± 0.5
	Reference[5]	56.8 ± 0.7	120 ± 1.2	15 ± 0.2	59.8 ± 0.7	13 ± 0.3	2.14 ± 0.08	14.8 ± 0.3	2.94 ± 0.06	19.5 ± 0.3	4.45 ± 0.09	15.2 ± 0.3
In-House Reference Materials												
MRB-29	**Cycled**	22.3 ± 1.8 (55)	50.3 ± 4.2 (55)	6.59 ± 0.57 (55)	28.9 ± 2.4 (55)	6.40 ± 0.57 (55)	1.90 ± 0.16 (55)	6.07 ± 0.50 (55)	0.929 ± 0.082 (55)	5.33 ± 0.46 (55)	1.052 ± 0.089 (55)	2.72 ± 0.24 (55)
MRB-32	**Cycled**	1.51 ± 0.13 (3)	4.17 ± 0.32 (3)	0.645 ± 0.044 (3)	3.17 ± 0.26 (3)	0.990 ± 0.056 (3)	0.269 ± 0.019 (3)	1.165 ± 0.050 (3)	0.1920 ± 0.0092 (3)	1.213 ± 0.050 (3)	0.244 ± 0.014 (3)	0.656 ± 0.031 (3)
NPD-1	**Cycled**	17.4 ± 1.6 (6)	36.9 ± 3.4 (6)	4.57 ± 0.44 (6)	19.4 ± 1.7 (6)	4.55 ± 0.43 (6)	1.32 ± 0.12 (6)	4.73 ± 0.45 (6)	0.781 ± 0.079 (6)	4.83 ± 0.44 (6)	1.013 ± 0.098 (6)	2.77 ± 0.25 (6)

Table 54.2. continued

		Tm	Yb	Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U
Procedural Blanks												
	Average	0.0005	0.003	0.0004	0.02	0.07	0.1	0.002	0.16	0.02	0.007	0.002
	2SD	0.0015	0.0059	0.0017	0.056	0.2	0.37	0.0032	0.25	0.064	0.025	0.0051
	n	54	54	54	51	54	54	53	50	52	54	53
	LLoD[1]	0.002	0.0089	0.0021	0.076	0.27	0.47	0.0052	0.41	0.084	0.032	0.0071
Inter-Laboratory Reference Materials												
AGV-2	**Cycled**	0.243 (1)	1.50 (1)	0.240 (1)	5.12 (1)	0.898 (1)	0.472 (1)	0.297 (1)	8.22 (1)	0.0760 (1)	4.30 (1)	1.02 (1)
	Compiled	0.265 ± 0.010 (12)	1.64 ± 0.05 (12)	0.255 ± 0.006 (12)	5.20 ± 0.12 (12)	0.948 ± 0.019 (12)	0.68 ± 0.14 (12)	0.315 ± 0.011 (12)	13.8 ± 1.6 (12)	0.07 ± 0.03 (12)	6.06 ± 0.18 (12)	1.87 ± 0.08 (12)
	Certificate	0.26 ± 0.04	1.6 ± 0.4	0.25 ± 0.02	5.08 ± 0.40	0.89 ± 0.16		0.27	13 ± 2		6.1 ± 1.2	1.88 ± 0.32
	Reference[4]	0.259	1.62 ± 0.01	0.247 ± 0.004								
BHVO-2	**Cycled**	0.353 ± 0.024 (6)	2.06 ± 0.15 (6)	0.296 ± 0.028 (6)	4.5 ± 0.5 (6)	1.26 ± 0.16 (6)	0.24 ± 0.06 (6)	0.024 ± 0.003 (6)	1.8 ± 0.4 (6)	0.026 ± 0.016 (6)	1.25 ± 0.12 (6)	0.47 ± 0.21 (6)
	Certificate		2.0 ± 0.4	0.28 ± 0.02	4.1 ± 0.6	1.4					1.20 ± 0.60	
	Reference[4]	0.341 ± 0.008	2.00 ± 0.01	0.274								
BIR-1	**Cycled**	0.28 ± 0.04 (3)	1.73 ± 0.24 (3)	0.27 ± 0.04 (3)	0.64 ± 0.11 (3)	0.074 ± 0.029 (3)	0.06 ± 0.12 (3)	0.0023 ± 0.0012 (3)	3.57 ± 0.28 (3)	0.03 ± 0.03 (3)	0.0367 ± 0.0023 (3)	0.0123 ± 0.0012 (3)
	Compiled	0.264 ± 0.008 (14)	1.67 ± 0.05 (14)	0.261 ± 0.006 (14)	0.65 ± 0.03 (14)	0.135 ± 0.009 (14)	0.08 ± 0.15 (14)	0.0030 ± 0.0026 (14)	3.9 ± 1.5 (12)	0.052 ± 0.029 (14)	0.034 ± 0.004 (14)	0.0136 ± 0.0027 (14)
	Certificate		1.7 ± 0.2	0.26	0.60 ± 0.16				3			
	Reference[5]	0.25 ± 0.01	1.64 ± 0.06	0.25 ± 0.01	0.6 ± 0.1	0.0310 ± 0.0078		0.0020 ± 0.0021	3.00 ± 0.53	0.0040 ± 0.0027	0.028 ± 0.001	0.009 ± 0.001
GSP-2	**Cycled**	0.31 ± 0.05 (2)	1.69 ± 0.29 (2)	0.24 ± 0.04 (2)	12.9 ± 2.2 (2)	0.98 ± 0.25 (2)	4.7 ± 2.8 (2)	1.54 ± 0.08 (2)	48.7 ± 1.9 (2)	0.033 ± 0.004 (2)	106 (1)[17]	2.49 ± 0.24 (2)
	Certificate	0.29 ± 0.04	1.6 ± 0.4	0.23 ± 0.06	14 ± 2			1.1	42 ± 6		105 ± 16	2.40 ± 0.38
	Reference[4]	0.298	1.64 ± 0.02	0.223								
GSR-1	**Cycled**	1.15 ± 0.15 (6)	7.8 ± 1.0 (6)	1.21 ± 0.14 (6)	5.7 ± 0.7 (6)	7.3 ± 0.9 (6)	8.4 ± 1.0 (6)	2.43 ± 0.28 (6)	33 ± 3 (6)	0.47 ± 0.06 (6)	55 ± 8 (6)	19.5 ± 2.8 (6)
	Certificate	1.06 ± 0.06	7.4 ± 0.2	1.15 ± 0.06	6.3 ± 0.5	7.2 ± 0.4	8.4 ± 0.2	1.93 ± 0.26	31.0 ± 1.3	0.53 ± 0.03	54.0 ± 1.3	18.8 ± 1.0
	Reference[6]	1.11 ± 0.04	7.68 ± 0.23	1.18 ± 0.04	5.84 ± 0.30	7.07 ± 0.30	7.87 ± 0.61		34.7 ± 0.6		56.4 ± 2.7	20.4 ± 1.1
GSR-2	**Cycled**	0.117 ± 0.008 (8)	0.73 ± 0.06 (8)	0.111 ± 0.009 (8)	2.48 ± 0.17 (8)	0.35 ± 0.22 (8)	0.42 ± 0.07 (8)	0.156 ± 0.014 (8)	10.3 ± 1.0 (8)	0.075 ± 0.026 (8)	2.51 ± 0.26 (8)	0.86 ± 0.11 (8)
	Compiled	0.119 ± 0.004 (13)	0.743 ± 0.029 (13)	0.113 ± 0.004 (13)	2.43 ± 0.10 (13)	0.432 ± 0.015 (13)	0.46 ± 0.16 (13)	0.155 ± 0.006 (13)	10.8 ± 1.3 (13)	0.113 ± 0.028 (13)	2.61 ± 0.28 (14)	0.88 ± 0.09 (14)
	Certificate	0.15	0.89 ± 0.07	0.12 ± 0.02	2.9 ± 0.3	0.46	0.47	0.16	11.3 ± 0.9	0.081 ± 0.010	2.60 ± 0.20	0.96 ± 0.09
	Reference[6]	0.12 ± 0.01	0.75 ± 0.01	0.11 ± 0.01	2.7 ± 0.1	0.37 ± 0.01	0.52 ± 0.06		9.92 ± 0.17		2.83 ± 0.02	0.90 ± 0.02
GSR-3	**Cycled**	0.241 ± 0.031 (4)	1.31 ± 0.17 (4)	0.173 ± 0.017 (4)	6.4 ± 0.6 (4)	4.5 ± 0.5 (4)	0.40 ± 0.06 (4)	0.038 ± 0.004 (4)	5.0 ± 0.5 (4)	0.016 ± 0.006 (4)	6.1 ± 0.8 (4)	1.48 ± 0.19 (4)
	Compiled	0.230 ± 0.009 (14)	1.24 ± 0.04 (14)	0.166 ± 0.004 (14)	6.07 ± 0.16 (14)	4.53 ± 0.12 (14)	0.43 ± 0.14 (14)	0.0362 ± 0.0032 (14)	4.58 ± 0.15 (14)	0.028 ± 0.005 (14)	5.84 ± 0.20 (14)	1.42 ± 0.06 (14)
	Certificate	0.28 ± 0.02	1.5 ± 0.2	0.19 ± 0.03	6.5 ± 0.4	4.3 ± 0.4	0.44	0.12	7.2 ± 1.2	0.045	6.00 ± 0.50	1.4 ± 0.2
	Reference[6]	0.26 ± 0.01	1.3 ± 0.07	0.18 ± 0.01	6.82 ± 0.16	4.4 ± 0.1			4.75 ± 0.19		6.26 ± 0.28	1.48 ± 0.06
RGM-1	**Cycled**	0.362 ± 0.008 (2)	2.365 ± 0.031 (2)	0.379 ± 0.004 (2)	5.58 ± 0.25 (2)	0.98 ± 0.05 (2)	1.27 ± 0.05 (2)	0.966 ± 0.023 (2)	22.46 ± 0.03 (2)	0.247 ± 0.027 (2)	14.2 ± 0.4 (2)	5.40 ± 0.17 (2)
	Compiled	0.376 ± 0.013 (14)	2.51 ± 0.07 (14)	0.399 ± 0.008 (14)	5.90 ± 0.13 (14)	1.00 ± 0.03 (14)	1.39 ± 0.13 (14)	1.009 ± 0.026 (14)	24.1 ± 2.0 (14)	0.261 ± 0.027 (14)	14.49 ± 0.29 (14)	5.57 ± 0.09 (14)
	Certificate		2.6 ± 0.6	0.41 ± 0.06		0.95 ± 0.20	1.50 ± 0.36		24 ± 6		15.1 ± 2.6	5.8 ± 1
	Reference[5]	0.36 ± 0.02	2.53 ± 0.04	0.39 ± 0.02	6.4 ± 0.2				24.0 ± 2.4		14 ± 2	5.5 ± 0.2
STM-1	**Cycled**	0.682 ± 0.026 (4)	4.33 ± 0.20 (4)	0.66 ± 0.03 (4)	27.9 ± 1.1 (4)	18.4 ± 0.6 (4)	3.21 ± 0.12 (4)	0.269 ± 0.015 (4)	17.3 ± 0.6 (4)	0.11 ± 0.03 (4)	30.6 ± 1.1 (4)	8.64 ± 0.27 (4)
	Certificate	0.7	4.4 ± 0.8	0.60 ± 0.22	28 ± 4	19 ± 24			18.0 ± 3.6	0.13	31 ± 6	9.1 ± 0.2
	Reference[5, 7]	0.65 ± 0.04	4.2 ± 0.2	0.63 ± 0.03	30 ± 2.1	17.5	3.7		17.0 ± 1.4		30.2 ± 0.6	8.6 ± 0.5
SY-4	**Cycled**	2.5 ± 0.4 (7)	15.4 ± 2.6 (7)	2.2 ± 0.4 (7)	10.3 ± 1.6 (7)	0.98 ± 0.21 (7)	0.21 ± 0.21 (7)	0.32 ± 0.05 (7)	10.0 ± 1.6 (7)	0.017 ± 0.016 (7)	1.3 ± 0.3 (7)	0.87 ± 0.29 (7)
	Compiled	2.39 ± 0.04 (14)	15.2 ± 0.3 (14)	2.18 ± 0.04 (14)	9.24 ± 0.23 (14)	0.915 ± 0.022 (14)	0.20 ± 0.13 (14)	0.306 ± 0.007 (14)	9.67 ± 0.24 (14)	0.029 ± 0.008 (14)	1.25 ± 0.04 (14)	0.815 ± 0.031 (14)
	Certificate	2.3 ± 0.1	14.8 ± 0.4	2.1 ± 0.1	10.6 ± 0.4	0.9 ± 0.1	0.2 - 15	0.2 - 0.5	10 ± 1	0.1 - 0.3	1.4 ± 0.2	0.80 ± 0.1
	Reference[5]	2.35 ± 0.05	15.7 ± 0.4	2.23 ± 0.05	9.4 ± 0.7	0.786	< 3		8.70 ± 0.37		1.3 ± 0.2	0.78 ± 0.09
In-House Reference Materials												
MRB-29	**Cycled**	0.408 ± 0.038 (55)	2.50 ± 0.22 (55)	0.375 ± 0.034 (55)	4.50 ± 0.40 (55)	0.88 ± 0.20 (55)	0.24 ± 0.13 (55)	0.085 ± 0.010 (55)	5.04 ± 0.66 (55)	0.034 ± 0.020 (54)	2.64 ± 0.27 (55)	0.640 ± 0.066 (55)
MRB-32	**Cycled**	0.1037 ± 0.0070 (3)	0.625 ± 0.022 (3)	0.0957 ± 0.0031 (3)	0.700 ± 0.057 (3)	0.196 ± 0.021 (3)	0.226 ± 0.032 (3)	0.0863 ± 0.0050 (3)	5.31 ± 0.54 (3)	2.80 ± 0.54 (3)	0.169 ± 0.015 (3)	0.0530 ± 0.0035 (3)
NPD-1	**Cycled**	0.427 ± 0.037 (6)	2.69 ± 0.23 (6)	0.410 ± 0.031 (6)	3.22 ± 0.29 (6)	0.55 ± 0.11 (6)	0.778 ± 0.084 (6)	0.252 ± 0.022 (6)	110 ± 14 (6)	0.122 ± 0.019 (6)	4.71 ± 0.59 (6)	1.53 ± 0.24 (6)

Table 54.3. Summary of trace element data obtained on the Elan 9000 ICP–MS using the IM-100 package (after an aqua regia leach).

		Li	Be	Sc	*Ti*[5]	V	Cr	Co	Ni	Cu	Zn	Ga	As	*Se*	Rb
Procedural Blanks															
	Average	0.009	0.007	0.14	*-0.81*	10.4	0.8	-0.009	0.12	0.43	1.6	-0.039	0.31	*0.1*	0.003
	2SD	0.032	0.02	0.32	*0.99*	7.4	1.8	0.018	0.16	0.88	2.8	0.033	0.53	*0.16*	0.011
	n	270	269	270	*270*	270	269	270	257	252	265	270	270	*270*	269
	LLoD[1]	0.056	0.037	0.62	*0.68*	21.5	3.6	0.017	0.36	1.75	5.9	0.011	1.11	*0.34*	0.02
Inter-Laboratory Reference Materials															
LKSD-1	**Cycled**	4.35 ± 0.48[2] (72)[3]	0.15 ± 0.04 (72)	2.53 ± 0.56 (72)	*420 ± 150 (72)*	21.5 ± 3.1 (72)	12.7 ± 1.5 (72)	7.82 ± 0.50 (72)	14.8 ± 1.9 (72)	43.9 ± 4.8 (72)	326 ± 25 (72)	2.17 ± 0.28 (72)	35.4 ± 2.8 (72)	*1.28 ± 0.24 (72)*	3.72 ± 0.44 (72)
	Compiled	4.39 ± 0.31 (19)	0.160 ± 0.029 (19)	2.98 ± 0.20 (19)	*538 ± 26 (19)*	22.1 ± 2.4 (19)	13.17 ± 0.84 (19)	7.65 ± 0.25 (19)	15.4 ± 1.0 (19)	41.1 ± 1.5 (19)	316 ± 12 (19)	2.298 ± 0.095 (19)	33.3 ± 1.3 (19)	*1.31 ± 0.19 (19)*	3.89 ± 0.16 (19)
	Certificate					27 ± 3	12 ± 2	9 ± 1	11 ± 1	44 ± 5	337 ± 11		30 ± 6		
	Reference[4, 5]				*620 ± 126*								39.5 ± 1.2	*1.089 ± 0.040*	
LKSD-2	**Cycled**	15.8 ± 1.7 (125)	0.72 ± 0.10 (125)	5.89 ± 0.81 (125)	*670 ± 200 (125)*	34.0 ± 6.8 (125)	28.3 ± 3.0 (125)	15.3 ± 0.9 (125)	26.1 ± 2.2 (125)	36.7 ± 5.4 (121)	197 ± 15 (125)	5.40 ± 0.72 (125)	9.7 ± 1.0 (125)	*1.19 ± 0.37 (125)*	17.6 ± 3.1 (125)
	Compiled	16.8 ± 1.2 (19)	0.789 ± 0.066 (19)	6.50 ± 0.36 (19)	*856 ± 45 (19)*	39.1 ± 5.8 (19)	29.9 ± 1.5 (19)	15.39 ± 0.70 (19)	27.8 ± 1.3 (19)	35.2 ± 1.2 (19)	199.4 ± 8.3 (19)	5.83 ± 0.23 (19)	9.96 ± 0.38 (19)	*0.95 ± 0.21 (19)*	20.62 ± 0.55 (19)
	Certificate					48 ± 10	29 ± 3	17 ± 1	23 ± 3	36 ± 3	200 ± 6		9 ± 3		
	Reference[4, 5]				*1010 ± 166*								10.8 ± 0.4	*0.684 ± 0.050*	
LKSD-3	**Cycled**	20.3 ± 3.2 (14)	0.63 ± 0.10 (14)	5.9 ± 1.1 (14)	*940 ± 310 (14)*	39.4 ± 8.9 (14)	48.8 ± 6.2 (14)	27.8 ± 1.7 (14)	47.4 ± 4.3 (14)	33.6 ± 1.5 (13)	133.5 ± 6.6 (14)	5.86 ± 0.87 (14)	24.7 ± 1.9 (14)	*0.74 ± 0.30 (14)*	25.0 ± 3.2 (14)
	Compiled	22.1 ± 1.7 (19)	0.704 ± 0.062 (19)	6.88 ± 0.46 (19)	*1,239 ± 85 (19)*	44.7 ± 7.3 (19)	53.5 ± 3.7 (19)	28.9 ± 1.7 (19)	50.9 ± 3.5 (19)	34.9 ± 1.8 (19)	142.6 ± 7.2 (19)	6.67 ± 0.32 (19)	25.6 ± 1.3 (19)	*0.77 ± 0.29 (19)*	27.7 ± 1.1 (19)
	Certificate					55 ± 13	51 ± 5	30 ± 2	44 ± 4	34 ± 3	139 ± 10		23 ± 6		
	Reference[4, 5]				*1410 ± 236*								28.6 ± 2.0	*0.59 ± 0.04*	
LKSD-4	**Cycled**	9.1 ± 1.9 (6)	0.440 ± 0.059 (6)	3.82 ± 0.92 (6)	*510 ± 170 (6)*	28.5 ± 5.5 (6)	20.6 ± 3.1 (6)	9.02 ± 0.97 (6)	33.3 ± 3.2 (6)	31.2 ± 2.8 (6)	187 ± 12 (6)	4.28 ± 0.70 (6)	14.50 ± 0.72 (6)	*2.52 ± 0.47 (6)*	10.1 ± 1.7 (6)
	Compiled	9.74 ± 0.86 (19)	0.461 ± 0.062 (19)	4.29 ± 0.33 (19)	*605 ± 30 (19)*	29.6 ± 3.7 (19)	20.7 ± 1.3 (19)	9.17 ± 0.44 (19)	33.6 ± 1.9 (19)	30.9 ± 1.1 (19)	188.0 ± 8.1 (19)	4.45 ± 0.14 (19)	14.41 ± 0.50 (19)	*2.51 ± 0.34 (19)*	11.00 ± 0.32 (19)
	Certificate					32 ± 10	21 ± 2	11 ± 1	32 ± 5	30 ± 3	189 ± 10		12 ± 3		
	Reference[4, 5]				*660 ± 86*								15.9 ± 0.8	*2.160 ± 0.042*	
STSD-1	**Cycled**	8.1 ± 1.3 (6)	0.422 ± 0.050 (6)	3.90 ± 0.87 (6)	*270 ± 110 (6)*	32.6 ± 5.9 (6)	26.1 ± 1.8 (6)	13.6 ± 1.1 (6)	20.4 ± 2.2 (6)	35.6 ± 3.5 (6)	170 ± 50 (6)	3.70 ± 0.46 (6)	20.0 ± 1.8 (6)	*1.98 ± 0.48 (6)*	7.59 ± 0.91 (6)
	Compiled	8.91 ± 0.62 (20)	0.439 ± 0.048 (20)	5.08 ± 0.33 (20)	*440 ± 23 (20)*	41.5 ± 6.5 (20)	29.5 ± 1.7 (20)	14.15 ± 0.71 (20)	22.4 ± 1.4 (20)	34.8 ± 1.2 (20)	167.0 ± 7.0 (20)	4.24 ± 0.16 (20)	20.05 ± 0.86 (20)	*1.86 ± 0.24 (20)*	8.96 ± 0.26 (20)
	Certificate					47 ± 11	28 ± 3	14 ± 2	18 ± 3	36 ± 2	165 ± 8		17 ± 5		
	Reference[4, 5]				*539 ± 130*								23.8 ± 0.6	*1.533 ± 0.046*	
STSD-2	**Cycled**	49.9 ± 2.9 (4)	3.11 ± 0.19 (4)	6.90 ± 0.70 (4)	*1,050 ± 220 (4)*	43 ± 10 (4)	51.07 ± 0.77 (4)	17.21 ± 0.87 (4)	53.1 ± 3.4 (4)	43.4 ± 2.5 (4)	219.0 ± 6.5 (4)	9.95 ± 0.72 (4)	36.6 ± 3.5 (4)	*0.89 ± 0.33 (4)*	31.8 ± 1.7 (4)
	Compiled	49.7 ± 4.5 (20)	3.10 ± 0.26 (20)	7.18 ± 0.53 (20)	*1,268 ± 78 (20)*	48.9 ± 7.9 (20)	53.2 ± 3.3 (20)	17.22 ± 0.90 (20)	54.7 ± 3.6 (20)	44.0 ± 1.7 (20)	227 ± 11 (20)	10.55 ± 0.44 (20)	37.0 ± 1.6 (20)	*0.56 ± 0.35 (20)*	33.2 ± 1.3 (20)
	Certificate					58 ± 14	50 ± 9	17 ± 1	47 ± 4	43 ± 3	216 ± 15		32 ± 8		
	Reference[4, 5]				*1720 ± 319*								42.1 ± 0.6	*0.439 ± 0.022*	
STSD-3	**Cycled**	17.9 ± 2.3 (2)	1.142 ± 0.084 (2)	3.7 ± 1.3 (2)	*280 ± 140 (2)*	38 ± 11 (2)	29.8 ± 5.6 (2)	13.4 ± 1.3 (2)	27.2 ± 3.0 (2)	36.7 ± 2.3 (2)	178.82 ± 0.34 (2)	4.90 ± 0.61 (2)	24.68 ± 0.03 (2)	*1.73 ± 0.41 (2)*	14.4 ± 2.3 (2)
	Compiled	19.1 ± 1.5 (19)	1.17 ± 0.10 (19)	4.39 ± 0.44 (19)	*426 ± 30 (19)*	46.2 ± 8.1 (19)	32.3 ± 2.4 (19)	13.65 ± 0.82 (19)	28.7 ± 1.9 (19)	37.3 ± 1.7 (19)	190 ± 10 (19)	5.59 ± 0.26 (19)	24.6 ± 1.2 (19)	*1.73 ± 0.33 (19)*	16.79 ± 0.44 (19)
	Certificate					61 ± 22	34 ± 6	14 ± 1	25 ± 3	38 ± 2	192 ± 11		22 ± 6		
	Reference[4, 5]				*614 ± 130*								28.3 ± 0.6	*1.472 ± 0.022*	
STSD-4	**Cycled**	9.14 (1)	0.319 (1)	3.49 (1)	*580 (1)*	39 (1)	30.4 (1)	9.76 (1)	25.4 (1)	61.8 (1)	79.6 (1)	3.41 (1)	11.83 (1)	*0.85 (1)*	6.64 (1)
	Compiled	8.94 ± 0.77 (19)	0.357 ± 0.046 (19)	4.43 ± 0.33 (19)	*923 ± 55 (19)*	44.3 ± 7.2 (19)	33.1 ± 2.1 (19)	10.18 ± 0.54 (19)	28.7 ± 1.9 (19)	64.1 ± 2.3 (19)	86.3 ± 4.2 (19)	4.22 ± 0.15 (19)	12.45 ± 0.52 (19)	*0.78 ± 0.27 (19)*	8.42 ± 0.35 (19)
	Certificate					51 ± 19	30 ± 6	11 ± 1	23 ± 2	66 ± 5	82 ± 8		11 ± 3		
	Reference[4, 5]				*1070 ± 202*								15.3 ± 1.0	*0.646 ± 0.026*	
TILL-1	**Cycled**	9.5 ± 2.0 (9)	0.522 ± 0.074 (9)	5.1 ± 1.0 (9)	*880 ± 350 (9)*	*42.4 ± 6.0 (9)*	27.9 ± 4.5 (9)	12.9 ± 1.5 (9)	20.9 ± 3.4 (9)	45.9 ± 2.8 (8)	71 ± 12 (9)	6.6 ± 1.3 (9)	16.7 ± 2.2 (9)	*0.46 ± 0.26 (9)*	6.2 ± 1.6 (9)
	Certificate					48 ± 16	30 ± 6	12 ± 2	18 ± 4	48 ± 4	70 ± 14		13 ± 8		
TILL-2	**Cycled**	32.5 ± 2.6 (5)	1.48 ± 0.11 (5)	4.81 ± 0.68 (5)	*930 ± 230 (5)*	*34.9 ± 2.8 (5)*	34.4 ± 3.0 (5)	12.99 ± 1.00 (5)	33.6 ± 3.3 (5)	140 ± 17 (5)	113 ± 11 (5)	7.6 ± 1.0 (5)	23.6 ± 1.5 (5)	*0.51 ± 0.51 (5)*	38.0 ± 5.3 (5)
	Certificate					38 ± 8	40 ± 6	13 ± 2	31 ± 6	149 ± 16	116 ± 12		22 ± 22		
TILL-3	**Cycled**	15.6 ± 2.6 (8)	0.36 ± 0.12 (8)	3.34 ± 0.87 (8)	*560 ± 280 (8)*	*27.8 ± 2.7 (8)*	60.1 ± 7.4 (8)	10.3 ± 1.0 (8)	32.0 ± 4.5 (8)	20.7 ± 1.6 (8)	39.8 ± 2.9 (8)	3.72 ± 0.60 (8)	83.8 ± 4.1 (8)	*0.30 ± 0.16 (8)*	7.9 ± 2.1 (8)
	Certificate					33 ± 10	73 ± 16	11 ± 2	32 ± 6	23 ± 2	43 ± 10		84 ± 24		
TILL-4	**Cycled**	19.5 ± 2.1 (6)	0.98 ± 0.12 (6)	4.42 ± 0.41 (6)	*1,070 ± 150 (6)*	*31.6 ± 7.1 (6)*	23.4 ± 1.6 (6)	5.93 ± 0.26 (6)	18.3 ± 1.4 (6)	233 ± 11 (6)	60.9 ± 2.7 (6)	6.10 ± 0.48 (6)	108.3 ± 4.8 (6)	*0.73 ± 0.28 (6)*	36.4 ± 1.6 (6)
	Certificate					38 ± 8	26 ± 4	6 ± 4	15 ± 4	254 ± 30	63 ± 12		102 ± 26		

Table 54.3. continued

		Sr	Y	Zr	Nb	Mo	*Rh (ppb)*	Ag	Cd	*In (ppb)*	Sn	Sb	*Te (ppb)*	Cs	Ba
Procedural Blanks															
	Average	0.08	0.0046	0.0022	0.0003	0.012	*-0.32*	0.003	0.003	*-0.01*	0.002	-0.0002	*5*	0.0008	0.037
	2SD	0.11	0.0096	0.0097	0.0038	0.015	*0.6*	0.011	0.0067	*0.88*	0.049	0.0059	*11*	0.00097	0.06
	n	264	270	249	269	257	*270*	267	254	*270*	257	269	*264*	270	264
	LLoD	0.25	0.019	0.0168	0.0059	0.034	*0.59*	0.02	0.013	*1.31*	0.075	0.0086	*22*	0.00225	0.128
Inter-Laboratory Reference Materials															
LKSD-1	**Cycled**	67.8 ± 3.5 (72)	10.7 ± 1.3 (72)	1.28 ± 0.57 (72)	0.71 ± 0.35 (72)	10.13 ± 0.59 (72)	*1.62 ± 0.81 (72)*	0.63 ± 0.05 (72)	1.35 ± 0.10 (72)	*495 ± 23 (72)*	3.32 ± 0.21 (72)	0.65 ± 0.11 (72)	*33 ± 44 (72)*	0.53 ± 0.06 (72)	97.1 ± 5.1 (72)
	Compiled	67.0 ± 2.6 (19)	11.43 ± 0.43 (19)	1.878 ± 0.076 (19)	1.005 ± 0.037 (19)	9.99 ± 0.34 (19)	*1.35 ± 0.82 (19)*	0.580 ± 0.019 (19)	1.303 ± 0.048 (19)	*477 ± 14 (19)*	3.15 ± 0.11 (19)	0.632 ± 0.025 (19)	*24 ± 13 (19)*	0.540 ± 0.020 (19)	94.7 ± 2.3 (19)
	Certificate					12 ± 4		0.6 ± 0.4	1.2 ± 0.6			1.2 ± 0.8			
	Reference[4, 5]	62 ± 8										1.06 ± 0.08	*35 ± 2*		85 ± 8
LKSD-2	**Cycled**	25.9 ± 4.8 (125)	29.0 ± 2.5 (125)	3.19 ± 0.72 (125)	1.50 ± 0.32 (125)	1.23 ± 0.11 (125)	*1.09 ± 0.93 (125)*	0.84 ± 0.07 (125)	0.86 ± 0.07 (125)	*62.9 ± 6.4 (125)*	1.38 ± 0.19 (125)	0.71 ± 0.13 (125)	*63 ± 13 (125)*	1.45 ± 0.26 (125)	217.1 ± 9.7 (125)
	Compiled	31.13 ± 0.84 (19)	29.85 ± 0.92 (19)	3.45 ± 0.11 (19)	1.586 ± 0.055 (19)	1.283 ± 0.057 (19)	*0.57 ± 0.72 (19)*	0.790 ± 0.022 (19)	0.841 ± 0.038 (19)	*66.1 ± 2.0 (19)*	1.490 ± 0.051 (19)	0.709 ± 0.025 (19)	*64 ± 12 (19)*	1.622 ± 0.041 (19)	224.3 ± 6.6 (19)
	Certificate					2.0 ± 1.4		0.8 ± 0.4	0.8 ± 0.4			1.2 ± 1.0			
	Reference[4, 5]	32 ± 12										1.02 ± 0.04	*88 ± 4*		211 ± 24
LKSD-3	**Cycled**	25.2 ± 8.4 (14)	18.2 ± 2.0 (14)	4.4 ± 1.1 (14)	1.96 ± 0.26 (14)	1.02 ± 0.08 (14)	*0.59 ± 0.53 (14)*	2.69 ± 0.24 (14)	0.54 ± 0.06 (14)	*45.2 ± 5.0 (14)*	1.11 ± 0.23 (14)	0.95 ± 0.07 (14)	*51 ± 14 (14)*	1.45 ± 0.25 (14)	166 ± 11 (14)
	Compiled	32.1 ± 1.4 (19)	19.93 ± 0.69 (19)	5.67 ± 0.19 (19)	2.207 ± 0.073 (19)	1.044 ± 0.032 (19)	*0.48 ± 0.87 (19)*	2.727 ± 0.099 (19)	0.554 ± 0.027 (19)	*48.3 ± 1.9 (19)*	1.240 ± 0.041 (19)	0.961 ± 0.034 (19)	*57 ± 16 (19)*	1.650 ± 0.051 (19)	176.2 ± 6.0 (19)
	Certificate					2.0 ± 1.8		2.4 ± 0.8	0.6 ± 0.6			1.4 ± 1.0			
	Reference[4, 5]	36 ± 16										1.30 ± 0.26	*66 ± 1*		169 ± 20
LKSD-4	**Cycled**	40.2 ± 3.5 (6)	17.1 ± 1.9 (6)	0.76 ± 0.15 (6)	1.11 ± 0.32 (6)	1.79 ± 0.12 (6)	*2.1 ± 1.4 (6)*	0.245 ± 0.017 (6)	2.07 ± 0.16 (6)	*54.9 ± 4.6 (6)*	3.30 ± 0.26 (6)	1.25 ± 0.13 (6)	*139 ± 16 (6)*	1.10 ± 0.19 (6)	140.7 ± 7.4 (6)
	Compiled	41.0 ± 1.5 (19)	17.24 ± 0.53 (19)	0.721 ± 0.039 (19)	1.234 ± 0.044 (19)	1.803 ± 0.057 (19)	*1.28 ± 0.88 (19)*	0.2343 ± 0.0093 (19)	2.042 ± 0.041 (19)	*55.2 ± 3.2 (19)*	3.271 ± 0.070 (19)	1.259 ± 0.042 (19)	*144 ± 14 (19)*	1.177 ± 0.023 (19)	141.2 ± 3.5 (19)
	Certificate					2.0 ± 1.2		0.2 ± 0.2	1.9 ± 1.0			1.5 ± 1.2			
	Reference[4, 5]	41 ± 10										1.64 ± 0.10	*188 ± 9*		135 ± 8
STSD-1	**Cycled**	29.1 ± 3.1 (6)	23.8 ± 2.4 (6)	0.60 ± 0.27 (6)	0.56 ± 0.12 (6)	1.12 ± 0.16 (6)	*0.90 ± 0.46 (6)*	0.352 ± 0.044 (6)	0.955 ± 0.091 (6)	*42.7 ± 4.1 (6)*	1.591 ± 0.091 (6)	2.42 ± 0.26 (6)	*75 ± 18 (6)*	1.09 ± 0.19 (6)	283 ± 13 (6)
	Compiled	31.3 ± 1.1 (20)	24.61 ± 0.79 (20)	0.335 ± 0.089 (20)	0.643 ± 0.029 (20)	1.119 ± 0.071 (20)	*0.76 ± 0.80 (20)*	0.332 ± 0.014 (20)	0.931 ± 0.049 (20)	*44.1 ± 2.2 (20)*	2.194 ± 0.052 (20)	2.396 ± 0.088 (20)	*73 ± 13 (20)*	1.304 ± 0.043 (20)	285.0 ± 10.0 (20)
	Certificate					2.0 ± 1.0		0.3 ± 0.2	0.8 ± 0.4			2 ± 2			
	Reference[4, 5]	28 ± 12										3.24 ± 0.32	*85 ± 3*		261 ± 18
STSD-2	**Cycled**	136.9 ± 6.7 (4)	20.5 ± 1.0 (4)	3.16 ± 0.58 (4)	2.04 ± 0.17 (4)	12.77 ± 0.51 (4)	*1.8 ± 2.4 (4)*	0.585 ± 0.041 (4)	0.925 ± 0.075 (4)	*84.6 ± 9.0 (4)*	1.50 ± 0.22 (4)	3.60 ± 0.37 (4)	*72 ± 19 (4)*	7.35 ± 0.84 (4)	107.0 ± 5.0 (4)
	Compiled	141.2 ± 5.9 (20)	20.99 ± 0.79 (20)	3.21 ± 0.13 (20)	2.04 ± 0.10 (20)	12.67 ± 0.66 (20)	*1.3 ± 1.5 (20)*	0.62 ± 0.23 (20)	0.910 ± 0.042 (20)	*84.8 ± 3.4 (20)*	1.521 ± 0.064 (20)	3.49 ± 0.11 (20)	*74 ± 18 (20)*	7.69 ± 0.19 (20)	111.5 ± 3.2 (20)
	Certificate					13 ± 4		0.5 ± 0.4	0.8 ± 0.6			2.6 ± 3.0			
	Reference[4, 5]	144 ± 14										4.62 ± 0.10	*89 ± 2*		110 ± 10
STSD-3	**Cycled**	62.6 ± 6.4 (2)	19.2 ± 1.5 (2)	0.72 ± 0.29 (2)	1.04 ± 0.11 (2)	6.25 ± 0.14 (2)	*1.75 ± 0.42 (2)*	0.463 ± 0.043 (2)	1.117 ± 0.026 (2)	*47.00 ± 0.28 (2)*	1.353 ± 0.038 (2)	3.041 ± 0.093 (2)	*58.0 ± 6.4 (2)*	2.71 ± 0.11 (2)	603 ± 92 (2)
	Compiled	66.0 ± 2.3 (19)	20.05 ± 0.57 (19)	0.524 ± 0.048 (19)	1.109 ± 0.043 (19)	6.21 ± 0.30 (19)	*0.8 ± 1.1 (19)*	0.433 ± 0.017 (19)	1.130 ± 0.057 (19)	*50.9 ± 1.8 (19)*	1.511 ± 0.056 (19)	3.21 ± 0.12 (19)	*73 ± 12 (19)*	3.13 ± 0.11 (19)	677 ± 26 (19)
	Certificate					7 ± 4		0.4 ± 0.2	1.0 ± 0.4			2.4 ± 2.4			
	Reference[4, 5]	67 ± 10										3.83 ± 0.08	*84 ± 4*		692 ± 124
STSD-4	**Cycled**	57.7 (1)	10.29 (1)	0.86 (1)	0.729 (1)	1.334 (1)	*1.4 (1)*	0.356 (1)	0.376 (1)	*25.8 (1)*	0.637 (1)	6.08 (1)	*39 (1)*	0.899 (1)	980 (1)
	Compiled	74.4 ± 2.8 (19)	12.28 ± 0.45 (19)	1.044 ± 0.042 (19)	0.967 ± 0.031 (19)	1.334 ± 0.067 (19)	*0.4 ± 1.3 (19)*	0.338 ± 0.019 (19)	0.380 ± 0.018 (19)	*30.1 ± 1.6 (19)*	0.807 ± 0.030 (19)	5.78 ± 0.16 (19)	*36 ± 16 (19)*	1.052 ± 0.031 (19)	1,361 ± 61 (17)
	Certificate					2.0 ± 1.2		0.3 ± 0.2	0.6 ± 0.6			3.6 ± 5.0			
	Reference[4, 5]	71 ± 20										7.02 ± 0.24	*44 ± 1*		1280 ± 162
TILL-1	**Cycled**	11.1 ± 3.1 (9)	13.8 ± 3.2 (9)	0.71 ± 0.26 (9)	1.24 ± 0.26 (9)	0.75 ± 0.11 (9)	*0.61 ± 0.97 (9)*	0.248 ± 0.032 (9)	0.242 ± 0.054 (9)	*52.0 ± 9.2 (9)*	1.03 ± 0.21 (9)	7.16 ± 0.69 (9)	*40 ± 15 (9)*	0.65 ± 0.18 (9)	83.4 ± 9.3 (9)
	Certificate					<2		0.2 ± 0.2	<0.2						84 ± 12
TILL-2	**Cycled**	12.5 ± 2.3 (5)	11.0 ± 2.1 (5)	4.73 ± 0.81 (5)	2.60 ± 0.19 (5)	12.8 ± 1.9 (5)	*1.9 ± 1.6 (5)*	0.262 ± 0.017 (5)	0.366 ± 0.030 (5)	*65.2 ± 7.4 (5)*	2.14 ± 0.19 (5)	0.501 ± 0.042 (5)	*39 ± 13 (5)*	7.00 ± 0.95 (5)	93.8 ± 8.8 (5)
	Certificate					11 ± 4		0.2 ± 0.2	0.3 ± 0.4						95 ± 14
TILL-3	**Cycled**	14.9 ± 4.8 (8)	5.9 ± 1.3 (8)	1.9 ± 1.2 (8)	0.71 ± 0.30 (8)	0.660 ± 0.051 (8)	*0.10 ± 0.68 (8)*	1.58 ± 0.19 (8)	0.110 ± 0.074 (8)	*16.2 ± 3.9 (8)*	1.28 ± 0.40 (8)	0.709 ± 0.058 (8)	*24 ± 21 (8)*	0.74 ± 0.27 (8)	38.4 ± 2.6 (8)
	Certificate					<2		1.6 ± 0.4	<0.2						43 ± 4
TILL-4	**Cycled**	9.29 ± 0.74 (6)	7.7 ± 1.5 (6)	4.34 ± 0.86 (6)	2.39 ± 0.33 (6)	15.68 ± 0.58 (6)	*2.9 ± 2.0 (6)*	0.198 ± 0.019 (6)	0.175 ± 0.010 (6)	*334 ± 15 (6)*	5.27 ± 0.37 (6)	0.739 ± 0.035 (6)	*221 ± 14 (6)*	8.51 ± 0.53 (6)	70.6 ± 1.5 (6)
	Certificate					14 ± 2		<0.2	<0.2						71 ± 8

Table 54.3. continued

		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Procedural Blanks															
	Average	0.009	0.017	0.0024	0.01	0.0028	0.0007	0.0028	0.00031	0.0015	0.00032	0.0012	0.00018	0.0008	0.00013
	2SD	0.019	0.037	0.0054	0.022	0.0053	0.0011	0.0044	0.00068	0.0026	0.00064	0.002	0.00038	0.0014	0.00047
	n	268	268	268	268	269	270	259	268	270	270	270	262	269	268
	LLoD	0.037	0.073	0.0104	0.043	0.0107	0.0023	0.0094	0.00134	0.0054	0.00128	0.0043	0.00075	0.003	0.00083
Inter-Laboratory Reference Materials															
LKSD-1	**Cycled**	10.9 ± 1.0 (72)	18.7 ± 2.2 (72)	2.99 ± 0.31 (72)	12.5 ± 1.2 (72)	2.58 ± 0.29 (72)	0.49 ± 0.06 (72)	2.42 ± 0.28 (72)	0.34 ± 0.04 (72)	1.77 ± 0.24 (72)	0.36 ± 0.05 (72)	1.01 ± 0.15 (72)	0.14 ± 0.02 (72)	0.90 ± 0.14 (72)	0.14 ± 0.02 (72)
	Compiled	11.26 ± 0.41 (19)	19.79 ± 0.67 (19)	3.13 ± 0.10 (19)	13.12 ± 0.31 (19)	2.73 ± 0.12 (19)	0.530 ± 0.022 (19)	2.58 ± 0.11 (19)	0.363 ± 0.016 (19)	1.915 ± 0.055 (19)	0.390 ± 0.013 (19)	1.098 ± 0.036 (19)	0.155 ± 0.006 (19)	0.989 ± 0.040 (19)	0.154 ± 0.005 (19)
	Certificate														
	Reference[4, 5]														
LKSD-2	**Cycled**	57.4 ± 4.5 (125)	97.7 ± 8.4 (122)[7]	14.2 ± 1.1 (125)	53.3 ± 4.2 (125)	9.29 ± 0.76 (125)	1.38 ± 0.11 (125)	7.95 ± 0.56 (125)	1.06 ± 0.08 (125)	5.20 ± 0.44 (125)	1.03 ± 0.09 (125)	2.89 ± 0.24 (125)	0.41 ± 0.03 (125)	2.58 ± 0.22 (125)	0.40 ± 0.03 (125)
	Compiled	58.4 ± 2.0 (19)	101.2 ± 3.3 (19)[8]	14.54 ± 0.29 (19)	54.6 ± 1.2 (19)	9.52 ± 0.24 (19)	1.437 ± 0.049 (19)	8.17 ± 0.34 (19)	1.100 ± 0.050 (19)	5.413 ± 0.098 (19)	1.076 ± 0.019 (19)	3.024 ± 0.076 (19)	0.427 ± 0.012 (19)	2.717 ± 0.088 (19)	0.418 ± 0.014 (19)
	Certificate														
	Reference[4, 5]														
LKSD-3	**Cycled**	41.5 ± 3.5 (14)	76.7 ± 7.4 (14)	10.22 ± 0.87 (14)	38.0 ± 3.7 (14)	6.49 ± 0.64 (14)	0.97 ± 0.12 (14)	5.44 ± 0.60 (14)	0.72 ± 0.09 (14)	3.40 ± 0.37 (14)	0.66 ± 0.08 (14)	1.82 ± 0.20 (14)	0.26 ± 0.03 (14)	1.63 ± 0.21 (14)	0.25 ± 0.03 (14)
	Compiled	44.4 ± 1.6 (19)	83.2 ± 2.5 (19)	10.94 ± 0.29 (19)	40.7 ± 1.1 (19)	7.00 ± 0.24 (19)	1.068 ± 0.040 (19)	5.88 ± 0.27 (19)	0.774 ± 0.039 (19)	3.739 ± 0.100 (19)	0.727 ± 0.014 (19)	2.021 ± 0.052 (19)	0.285 ± 0.009 (19)	1.805 ± 0.066 (19)	0.273 ± 0.010 (19)
	Certificate														
	Reference[4, 5]														
LKSD-4	**Cycled**	21.7 ± 2.4 (6)	40.2 ± 4.8 (6)	5.78 ± 0.66 (6)	22.7 ± 2.2 (6)	4.28 ± 0.35 (6)	0.918 ± 0.089 (6)	4.05 ± 0.30 (6)	0.561 ± 0.045 (6)	2.96 ± 0.28 (6)	0.597 ± 0.060 (6)	1.71 ± 0.16 (6)	0.245 ± 0.019 (6)	1.59 ± 0.14 (6)	0.245 ± 0.023 (6)
	Compiled	22.09 ± 0.68 (19)	41.3 ± 1.4 (19)	5.89 ± 0.13 (19)	23.17 ± 0.65 (19)	4.34 ± 0.14 (19)	0.937 ± 0.026 (19)	4.14 ± 0.15 (19)	0.580 ± 0.024 (19)	3.026 ± 0.077 (19)	0.611 ± 0.016 (19)	1.747 ± 0.042 (19)	0.252 ± 0.009 (19)	1.640 ± 0.063 (19)	0.252 ± 0.008 (19)
	Certificate														
	Reference[4, 5]														
STSD-1	**Cycled**	21.9 ± 2.2 (6)	36.1 ± 4.3 (6)	6.15 ± 0.71 (6)	25.2 ± 3.0 (6)	5.11 ± 0.56 (6)	1.08 ± 0.10 (6)	5.25 ± 0.56 (6)	0.740 ± 0.079 (6)	3.85 ± 0.46 (6)	0.779 ± 0.069 (6)	2.22 ± 0.22 (6)	0.313 ± 0.033 (6)	2.04 ± 0.20 (6)	0.321 ± 0.030 (6)
	Compiled	22.97 ± 0.96 (20)	39.1 ± 1.3 (20)	6.49 ± 0.14 (20)	26.66 ± 0.89 (20)	5.42 ± 0.17 (20)	1.143 ± 0.040 (20)	5.47 ± 0.24 (20)	0.770 ± 0.026 (20)	4.03 ± 0.11 (20)	0.814 ± 0.028 (20)	2.321 ± 0.069 (20)	0.327 ± 0.007 (20)	2.109 ± 0.076 (20)	0.334 ± 0.009 (20)
	Certificate														
	Reference[4, 5]														
STSD-2	**Cycled**	32.6 ± 2.4 (4)	52.0 ± 4.8 (4)	7.42 ± 0.61 (4)	27.7 ± 1.8 (4)	5.22 ± 0.40 (4)	1.287 ± 0.058 (4)	5.02 ± 0.30 (4)	0.709 ± 0.037 (4)	3.65 ± 0.28 (4)	0.701 ± 0.063 (4)	1.957 ± 0.084 (4)	0.271 ± 0.015 (4)	1.731 ± 0.076 (4)	0.263 ± 0.012 (4)
	Compiled	34.9 ± 1.3 (20)	56.7 ± 2.0 (20)	7.97 ± 0.21 (20)	29.87 ± 0.64 (20)	5.59 ± 0.17 (20)	1.321 ± 0.041 (20)	5.24 ± 0.17 (20)	0.742 ± 0.025 (20)	3.78 ± 0.13 (20)	0.732 ± 0.020 (20)	2.017 ± 0.075 (20)	0.283 ± 0.007 (20)	1.792 ± 0.073 (20)	0.271 ± 0.009 (20)
	Certificate														
	Reference[4, 5]														
STSD-3	**Cycled**	21.8 ± 1.1 (2)	37.0 ± 3.0 (2)	5.70 ± 0.22 (2)	22.6 ± 1.6 (2)	4.444 ± 0.100 (2)	1.019 ± 0.030 (2)	4.449 ± 0.059 (2)	0.629 ± 0.015 (2)	3.206 ± 0.087 (2)	0.634 ± 0.010 (2)	1.783 ± 0.064 (2)	0.251 ± 0.005 (2)	1.63 ± 0.15 (2)	0.252 ± 0.004 (2)
	Compiled	24.53 ± 0.70 (19)	42.0 ± 1.5 (19)	6.30 ± 0.22 (19)	24.72 ± 0.77 (19)	4.82 ± 0.17 (19)	1.068 ± 0.039 (19)	4.72 ± 0.21 (19)	0.661 ± 0.027 (19)	3.40 ± 0.10 (19)				1.697 ± 0.077 (19)	0.266 ± 0.012 (19)
	Certificate														
	Reference[4, 5]														
STSD-4	**Cycled**	12.84 (1)	25.3 (1)	3.37 (1)	13.43 (1)	2.65 (1)	0.692 (1)	2.62 (1)	0.357 (1)	1.857 (1)	0.364 (1)	1.033 (1)	0.1408 (1)	0.901 (1)	0.1334 (1)
	Compiled	15.41 ± 0.48 (19)	30.58 ± 0.87 (19)	4.040 ± 0.094 (19)	15.96 ± 0.45 (19)	3.132 ± 0.099 (19)	0.783 ± 0.060 (19)	3.05 ± 0.12 (19)	0.427 ± 0.016 (19)	2.209 ± 0.055 (19)	0.433 ± 0.011 (19)	1.209 ± 0.041 (19)	0.170 ± 0.007 (19)	1.077 ± 0.033 (19)	0.163 ± 0.005 (19)
	Certificate														
	Reference[4, 5]														
TILL-1	**Cycled**	19.9 ± 4.6 (9)	55 ± 11 (9)	5.3 ± 1.2 (9)	20.7 ± 4.6 (9)	4.01 ± 0.88 (9)	0.80 ± 0.17 (9)	3.80 ± 0.81 (9)	0.55 ± 0.12 (9)	2.81 ± 0.63 (9)	0.53 ± 0.13 (9)	1.43 ± 0.35 (9)	0.198 ± 0.047 (9)	1.22 ± 0.31 (9)	0.171 ± 0.043 (9)
	Certificate														
TILL-2	**Cycled**	28.4 ± 9.2 (5)	68 ± 18 (5)	6.8 ± 2.0 (5)	25.3 ± 7.4 (5)	4.8 ± 1.4 (5)	0.73 ± 0.15 (5)	4.2 ± 1.0 (5)	0.58 ± 0.13 (5)	2.69 ± 0.51 (5)	0.454 ± 0.082 (5)	1.13 ± 0.21 (5)	0.151 ± 0.027 (5)	0.91 ± 0.16 (5)	0.125 ± 0.021 (5)
	Certificate														
TILL-3	**Cycled**	13.7 ± 2.9 (8)	28.8 ± 6.2 (8)	3.32 ± 0.72 (8)	12.6 ± 2.7 (8)	2.24 ± 0.48 (8)	0.446 ± 0.090 (8)	1.97 ± 0.35 (8)	0.260 ± 0.053 (8)	1.20 ± 0.24 (8)	0.222 ± 0.043 (8)	0.58 ± 0.12 (8)	0.078 ± 0.017 (8)	0.48 ± 0.10 (8)	0.068 ± 0.015 (8)
	Certificate														
TILL-4	**Cycled**	26.0 ± 4.9 (6)	48.6 ± 9.9 (6)	5.4 ± 1.2 (6)	19.2 ± 4.7 (6)	3.60 ± 0.84 (6)	0.479 ± 0.097 (6)	3.07 ± 0.69 (6)	0.429 ± 0.095 (6)	1.97 ± 0.39 (6)	0.331 ± 0.062 (6)	0.85 ± 0.15 (6)	0.115 ± 0.018 (6)	0.71 ± 0.12 (6)	0.096 ± 0.016 (6)
	Certificate														

Table 54.3. continued

		Hf	Ta (ppb)	W	*Ir (ppb)*	*Pt (ppb)*	Au (ppb)	Hg	Tl	Pb	Bi	Th	U
Procedural Blanks													
	Average	0.0007	0.23	0.0029	*0.79*	*1.3*	0.2	0.0054	0.0015	0.08	0.0014	0.006	0.0011
	2SD	0.0014	0.44	0.0061	*0.87*	*2.6*	4	0.0076	0.0023	0.13	0.0051	0.011	0.002
	n	263	270	258	*270*	*270*	253	269	265	256	264	269	266
	LLoD	0.0027	0.89	0.0121	*2.09*	*5.2*	6.2	0.0168	0.005	0.28	0.009	0.021	0.0042
Inter-Laboratory Reference Materials													
LKSD-1	**Cycled**	0.04 ± 0.01 (72)	4.2 ± 1.1 (72)	0.65 ± 0.27 (72)	*0.65 ± 0.46 (72)*	*0.8 ± 1.5 (72)*	5.9 ± 4.2 (66)	0.12 ± 0.01 (72)	0.23 ± 0.02 (72)	83.2 ± 6.1 (72)	0.95 ± 0.12 (72)	1.42 ± 0.26 (72)	9.03 ± 0.58 (72)
	Compiled	0.054 ± 0.007 (19)	6.11 ± 0.66 (19)	0.646 ± 0.030 (19)	*1.61 ± 0.63 (19)*	*4.7 ± 2.6 (19)*	6.9 ± 3.2 (17)	0.095 ± 0.031 (19)	0.226 ± 0.010 (19)	79.0 ± 2.7 (19)	0.891 ± 0.028 (19)	1.480 ± 0.050 (19)	8.74 ± 0.33 (19)
	Certificate							0.11		84 ± 10			
	Reference[4, 5]										0.95 ± 0.06		
LKSD-2	**Cycled**	0.08 ± 0.02 (125)	7.7 ± 4.6 (125)	0.43 ± 0.12 (125)	*0.78 ± 0.99 (125)*	*2.0 ± 2.5 (125)*	3.6 ± 7.3 (115)	0.17 ± 0.02 (125)	0.30 ± 0.03 (125)	39.7 ± 3.8 (125)	1.17 ± 0.19 (125)	8.2 ± 1.2 (125)	6.60 ± 0.48 (125)
	Compiled	0.074 ± 0.009 (19)	9.5 ± 2.1 (19)	0.509 ± 0.025 (19)	*0.75 ± 0.37 (19)*	*0.8 ± 1.8 (19)*	11.2 ± 3.9 (17)	0.156 ± 0.020 (19)	0.305 ± 0.010 (19)	40.3 ± 1.0 (19)	1.158 ± 0.032 (19)	9.36 ± 0.25 (19)	6.58 ± 0.17 (19)
	Certificate							0.16		40 ± 7			
	Reference[4, 5]										1.07 ± 0.04		
LKSD-3	**Cycled**	0.09 ± 0.02 (14)	5.7 ± 1.2 (14)	0.36 ± 0.12 (14)	*0.48 ± 0.60 (14)*	*1.4 ± 1.6 (14)*	5.4 ± 6.9 (10)	0.29 ± 0.05 (14)	0.29 ± 0.03 (14)	24.9 ± 2.5 (14)	3.04 ± 0.21 (14)	7.7 ± 1.7 (14)	3.76 ± 0.27 (14)
	Compiled	0.101 ± 0.013 (19)	6.5 ± 1.2 (19)	0.462 ± 0.019 (19)	*0.66 ± 0.45 (19)*	*0.9 ± 1.6 (19)*	5.3 ± 2.8 (17)	0.270 ± 0.040 (19)	0.312 ± 0.012 (19)	24.97 ± 0.78 (19)	3.110 ± 0.082 (19)	8.88 ± 0.29 (19)	3.91 ± 0.11 (19)
	Certificate							0.29		26 ± 5			
	Reference[4, 5]										2.81 ± 0.18		
LKSD-4	**Cycled**	0.031 ± 0.012 (6)	6.0 ± 2.7 (6)	0.28 ± 0.18 (6)	*0.80 ± 0.89 (6)*	*1.5 ± 2.9 (6)*	2.3 ± 7.0 (5)	0.189 ± 0.016 (6)	0.439 ± 0.035 (6)	94.2 ± 5.0 (6)	0.509 ± 0.045 (6)	1.76 ± 0.26 (6)	30.0 ± 2.6 (5)[9]
	Compiled	0.026 ± 0.005 (19)	5.8 ± 1.1 (19)	0.652 ± 0.019 (19)	*0.58 ± 0.54 (19)*	*0.1 ± 1.4 (19)*	4.4 ± 2.7 (17)	0.194 ± 0.012 (19)	0.447 ± 0.021 (19)	92.6 ± 2.0 (19)	0.504 ± 0.015 (19)	2.094 ± 0.054 (19)	31.4 ± 2.5 (15)[10]
	Certificate							0.19		93 ± 8			
	Reference[4, 5]										0.48 ± 0.006		
STSD-1	**Cycled**	0.038 ± 0.009 (6)	8.0 ± 5.3 (6)	0.33 ± 0.47 (6)	*0.78 ± 0.60 (6)*	*1.1 ± 1.8 (6)*	9.4 ± 8.1 (6)	0.127 ± 0.015 (6)	0.252 ± 0.033 (6)	36.2 ± 3.0 (6)	0.455 ± 0.031 (6)	0.84 ± 0.11 (6)	7.14 ± 0.46 (6)
	Compiled	0.025 ± 0.006 (20)	7.0 ± 1.1 (20)	0.211 ± 0.010 (20)	*0.62 ± 0.62 (20)*	*0.2 ± 1.1 (20)*	19.8 ± 8.9 (18)	0.116 ± 0.009 (20)	0.280 ± 0.014 (20)	36.0 ± 1.1 (20)	0.459 ± 0.017 (20)	1.010 ± 0.023 (20)	7.04 ± 0.25 (20)
	Certificate							0.11		34 ± 4			
	Reference[4, 5]										0.45 ± 0.06		
STSD-2	**Cycled**	0.059 ± 0.017 (4)	11.7 ± 8.6 (4)	3.1 ± 1.1 (4)	*0.8 ± 1.6 (4)*	*2.7 ± 3.7 (4)*	4.5 ± 5.2 (3)	0.105 ± 0.016 (4)	0.271 ± 0.017 (4)	69.9 ± 1.9 (4)	3.81 ± 0.18 (4)	9.38 ± 0.83 (4)	15.54 ± 0.45 (4)
	Compiled	0.054 ± 0.006 (20)	9.0 ± 1.1 (20)	4.37 ± 0.12 (20)	*0.64 ± 0.51 (20)*	*1.5 ± 1.4 (20)*	3.7 ± 2.7 (17)	0.135 ± 0.027 (19)	0.276 ± 0.009 (20)	68.5 ± 1.6 (20)	3.801 ± 0.092 (20)	10.60 ± 0.30 (20)	15.64 ± 0.42 (20)
	Certificate							0.046		66 ± 7			
	Reference[4, 5]										3.86 ± 0.06		
STSD-3	**Cycled**	0.033 ± 0.009 (2)	9.9 ± 4.0 (2)	1.4 ± 1.1 (2)	*0.4 ± 1.3 (2)*	*1.4 ± 2.5 (2)*	10 ± 34 (2)	0.123 ± 0.024 (2)	0.278 ± 0.023 (2)	41.65 ± 0.55 (2)	1.306 ± 0.041 (2)	1.676 ± 0.099 (2)	8.40 ± 0.27 (2)
	Compiled	0.023 ± 0.005 (19)	6.19 ± 0.98 (19)	1.707 ± 0.046 (19)	*0.62 ± 0.53 (19)*	*0.3 ± 1.8 (19)*	4.5 ± 2.9 (17)	0.125 ± 0.014 (19)	0.308 ± 0.012 (19)	41.3 ± 1.6 (19)	1.342 ± 0.049 (19)	2.007 ± 0.076 (19)	8.35 ± 0.31 (19)
	Certificate							0.090		39 ± 5			
	Reference[4, 5]										1.35 ± 0.06		
STSD-4	**Cycled**	0.0296 (1)	5.00 (1)	0.250 (1)	*1.30 (1)*	*2.2 (1)*	-3.9 (1)	0.90 (1)	0.1275 (1)	12.6 (1)	0.223 (1)	1.39 (1)	1.96 (1)
	Compiled	0.026 ± 0.005 (19)	4.29 ± 0.80 (19)	0.230 ± 0.010 (19)	*0.61 ± 0.51 (19)*	*0.4 ± 1.5 (19)*	3.3 ± 3.2 (17)	0.81 ± 0.11 (19)	0.144 ± 0.008 (19)	13.20 ± 0.33 (19)	0.198 ± 0.008 (19)	2.548 ± 0.055 (19)	2.847 ± 0.058 (19)
	Certificate							0.93		13 ± 4			
	Reference[4, 5]										0.21 ± 0.04		
TILL-1	**Cycled**	0.025 ± 0.007 (9)	5.3 ± 2.6 (9)	0.188 ± 0.020 (9)	*0.83 ± 0.90 (9)*	*1.1 ± 3.0 (9)*	28 ± 78 (9)	0.103 ± 0.017 (9)	0.131 ± 0.034 (9)	15.7 ± 8.6 (9)	2.02 ± 0.24 (9)	3.31 ± 0.91 (9)	0.90 ± 0.14 (9)
	Certificate							0.092 ± 0.022		12 ± 2	< 3		
TILL-2	**Cycled**	0.080 ± 0.018 (5)	8.5 ± 4.8 (5)	2.06 ± 0.28 (5)	*0.84 ± 0.98 (5)*	*1.9 ± 2.4 (5)*	2.7 ± 1.8 (5)	0.116 ± 0.015 (5)	0.358 ± 0.036 (5)	23.68 ± 0.93 (5)	5.18 ± 0.25 (5)	10.7 ± 2.9 (5)	3.14 ± 0.42 (5)
	Certificate							0.074 ± 0.026		21 ± 4	4 ± 4		
TILL-3	**Cycled**	0.046 ± 0.027 (8)	2.7 ± 2.1 (8)	0.22 ± 0.13 (8)	*0.70 ± 0.70 (8)*	*1.1 ± 3.0 (8)*	8 ± 17 (8)	0.115 ± 0.024 (8)	0.072 ± 0.020 (8)	17.3 ± 1.2 (8)	0.302 ± 0.019 (8)	2.87 ± 0.78 (8)	1.19 ± 0.13 (8)
	Certificate							0.107 ± 0.030		16 ± 2	< 3		
TILL-4	**Cycled**	0.088 ± 0.022 (6)	13 ± 15 (6)	157.8 ± 8.0 (6)	*0.85 ± 0.65 (6)*	*1.3 ± 2.4 (6)*	10 ± 11 (6)	2.98 ± 0.75 (6)	0.425 ± 0.023 (6)	39.7 ± 2.4 (6)	45.9 ± 2.4 (6)	11.5 ± 1.2 (6)	2.57 ± 0.28 (6)
	Certificate							0.039 ± 0.024		36 ± 6	44 ± 8		

Table 54.4. Estimated upper limits for major and trace element analyses on the Elan 9000 ICP–MS (ppm).

Element	IM-101	IM-100 Digest	IM-100 ARD
Li		4000	2600
Be		19000	5000
Sc		400	100
Ti		12000	*2800*
V		500	270
Cr		600	150
Co		400	140
Ni		2000	3000
Cu		800	400
Zn		2400	700
Ga		500	150
As			1000
Se			*6000*
Rb	300	400	100
Sr	2300	2700	700
Y	280	300	90
Zr	600	600	100
Nb	200	230	60
Mo		1500	400
Rh			*60*
Ag			130
Cd		900	600
In			*50*
Sn		400	190
Sb		250	170
Te			*1200*
Cs	120	150	40
Ba	*2400*	2900	900
La	210	230	70
Ce	310	300	110
Pr	120	130	40
Nd	1000	1000	300
Sm	800	800	260
Eu	270	260	80
Gd	600	500	200
Tb	130	120	40
Dy	500	400	170
Ho	120	120	40
Er	600	500	180
Tm	120	100	40
Yb	700	600	110
Lu	120	260	40
Hf	400	400	130
Ta	120	120	60
W		400	170
Ir			*80*
Pt			*220*
Au			*220*
Hg			600
Tl		160	70
Pb		400	230
Bi		170	50
Th	55	50	30
U	55	60	30

Italics: Elements added to the IM-101 and IM-100 packages for digested and aqua regia leached samples.

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Metric Conversion Table

Conversion from SI to Imperial			**Conversion from Imperial to SI**		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

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